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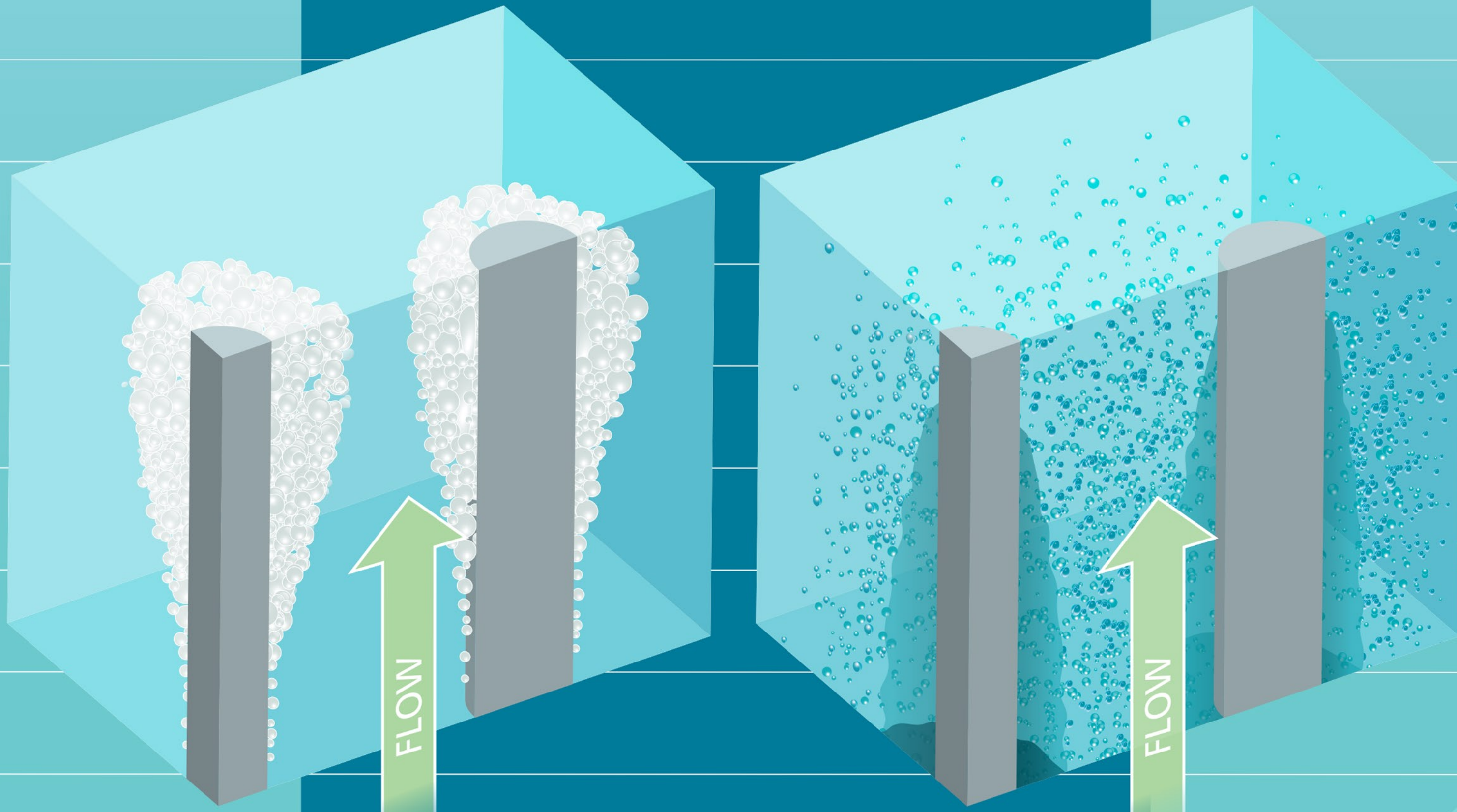

CRITICAL HEAT FLUX DATA USED TO GENERATE THE 2006 GROENEVELD CRITICAL HEAT FLUX LOOKUP TABLES

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Critical Heat Flux Data Used to Generate the 2006 Groeneveld Lookup Tables

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ABSTRACT

This report contains a compilation of over 25,000 critical heat flux (CHF) data points obtained in water-cooled tubes that were used to derive the 2006 Groeneveld CHF lookup table. This compilation is based on 62 data sets that have been obtained during the past 60 years. This NUREG report describes the pertinent experimental details and possible concerns for these data sets. It also discusses the applicability and validity of the CHF lookup table to reactor conditions of interest and includes a graphical comparison of the ranges of conditions covered by these primary data and subsequently obtained supplementary data sets.

FOREWORD

The history of critical heat flux (CHF) is the history of its experimental data. There are few collections of those data from as wide a range of experiments as those given in the Groeneveld lookup tables, and there are likely few individuals who have had as much history as Dr. Groeneveld himself. The U.S. Nuclear Regulatory Commission (NRC) created this NUREG report for two purposes:

1) to define and capture the all-important data that comprise the Groeneveld lookup table, including detailed data from over 60 data sets that span over 65 years of data collection

2) to include many of Dr. Groeneveld's personal insights into the history, current state, and future of CHF prediction—information that does not appear in any textbook or journal article and is often known only by those who have tremendous experience in the field

I am grateful to the NRC and particularly to Andrew Ireland and the Office of Research for supporting this work and to Dr. Groeneveld for being willing to create it. It not only provides key information on very important data but also fills in much of the undocumented history of CHF.

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1 INTRODUCTION

Various prediction methods for the critical heat flux (CHF) have been proposed during the past 70 years. The earliest prediction methods were primarily empirical. These crude empirical correlations lacked any physical basis and had a limited range of application. Subsequently, a large number of phenomenological equations or physical models for CHF were developed; many of these models were subsequently used in reactor safety analysis codes. Physical models and phenomenological equations, however, depend on the mechanisms controlling the CHF, which changes with flow regime. These changes necessitate the use of a combination of different models, equations, or correlations for predicting the CHF during typical reactor scenarios. Because of this and because of the proliferation of CHF equations and correlations (over 500 CHF correlations are currently available for water-cooled tubes only), a more universal CHF prediction methodology was required. Hence, lookup tables (LUTs) for predicting the CHF in water-cooled tubes were subsequently derived.

The CHF LUT can be thought of as a normalized CHF databank. Compared to other available prediction methods, the LUT approach has the following advantages:

- The approach has greater accuracy.
- It has a wider range of applicability.
- It can predict the correct asymptotic trend(s).
- It requires less computing time.
- It can be updated if additional data become available.

Although LUTs were initially developed for tubes and have been successfully used in subchannel codes, the greatest potential for their application is in predicting the consequences of postulated loss-of-coolant accidents. Applying the LUTs to transient heat transfer in bundles requires the use of adjustment factors to correct for geometry, flux shape, and possibly transient effects. Here the advantages of the LUT technique (wide range of application, greater accuracy, and more efficiency in computing) are particularly important to the user.

Section 2 of this report discusses the types of CHF experiments and CHF detection methods used during the past 70 years and various factors that could affect the uncertainty in the CHF measurements. Section 3 provides the background to CHF prediction methods in general and CHF LUTs specifically, while Section 4 describes the database for the 2006 CHF LUT and explains how the CHF data were obtained. Section 5 describes the methodology for deriving the CHF LUT.

Section 6 discusses the database coverage of the present and expanded database (data identified subsequent to the 2006 CHF LUT derivation) and describes some limitations in the CHF LUT and possible future improvements.

2 CRITICAL HEAT FLUX MEASUREMENTS AND UNCERTAINTIES

2.1 Early Flow Boiling Testing

Before the advent of nuclear reactors, the need for CHF measurements was not urgent because most boiling processes in which CHF was encountered were temperature controlled (e.g., heat exchanger tubes in fossil-fueled boilers). However, water-cooled nuclear reactors, which are limited in power by the CHF occurrence, are basically heat-flux-controlled systems. Hence, exceeding the CHF can have serious consequences, particularly for pressurized-water reactors. For this reason, most of the countries with an interest in nuclear energy became active in CHF measurements by the mid-1900s. In the United States, McAdams et al. (1949) and Jens and Lottes (1951) reported early flow boiling CHF measurements in simple geometries, such as electrically heated tubes, annuli, or rectangular channels (see also the early review of CHF studies by DeBortoli (1958)). CHF experimentation expanded greatly in the 1960s and 1970s in parallel with the worldwide construction of water-cooled nuclear reactors.

2.2 Critical Heat Flux Detection Methods

CHF is typically characterized by a noticeable increase in surface temperature in response to a small change in heat flux. This change in temperature can be very drastic (for example, under pressurized-water reactor conditions referred to as “fast dryout” (Groeneveld, 1986)), or this change can be gradual (for example, under boiling-water reactor conditions, referred to as “slow dryout”). Over the past 70 years, CHF experimenters have used many different CHF detection methods. The sections below summarize the four main methods.

Visual

Early CHF papers identified the CHF as the heat flux at which the test section “started to redden visually.” Some early researchers (e.g., Hood and Isakoff, 1962) used this method. Although this method could work well for so-called “fast dryouts” or departure from nucleate boiling (DNB) at subcooled CHF conditions, the slow dryouts, which are typical under boiling-water reactor conditions, would result in only modest temperature excursions that do not result in a discoloration of the heated surface.

Physical Burnout

At high flows and high subcoolings, the CHF is typically very high, making it difficult to switch off the power at CHF before failure of the test section. Several investigators have reported that their CHF corresponded frequently to a physical burnout at the CHF occurrence (e.g., Hood and Isakoff, 1962; Pabisz and Bergles, 1996).

Change in Test-Section Resistance

The test-section material used in most CHF experiments is either Inconel or stainless steel. Inconel has a very low-temperature coefficient of resistance compared to stainless steel, which has a much higher value. The use of a stainless steel test section as one leg of a Wheatstone bridge allows detection of a CHF when the change in test-section resistance caused by a significant temperature excursion results in an imbalance in the Wheatstone bridge, triggering a power supply trip. Dell et al. (1969), Matzner et al. (1965), Hewitt et al. (1965), and others reported this CHF detection method.

Test-Section Thermocouples

The most common method for detecting CHF is the use of thermocouples attached to the downstream end of the heated length of the test section. This method is most effective for most types of CHF occurrences except for very fast temperature excursions, in which a method based on detecting a change in test-section resistance may be more effective. For very slow dryouts, this method may not always be reliable because of the absence of a noticeable dryout temperature excursion. Here, a more reliable method is based on monitoring the change in the slope of $\Delta T_w/\Delta q$ (Groeneveld, 1986).

In some cases, the CHF was actually a "byproduct" of a film boiling experiment in which detailed wall temperature distributions were measured; for any given heat flux, the CHF quality was either assumed to be the quality where the first rise in surface temperature was detected, or the CHF quality was defined as the average of the last pre-CHF quality and the (subsequent) first post-CHF quality. Examples of this type of CHF measurement are Era et al. (1966), Bennett et al. (1967), and Herkenrath et al. (1967); the latter two sources refer to CHF validation data sets.

2.3 Uncertainties in Critical Heat Flux

CHF is primarily a function of flow conditions and test-section geometry. Because the LUT is based only on CHF measurements obtained in a tubular geometry, this section does not discuss how noncircular geometries affect CHF. In CHF experiments, the CHF is a function of the following primary parameters: (1) pressure (either at the start of the heated length or at the CHF location), (2) inlet temperature, (3) mass flow, (4) diameter, and (5) heated length. Several experimenters (e.g., Lee and Obertelli, 1963; Lee, 1965) have shown that the primary parameters, heated length and inlet temperature, can be replaced by thermodynamic quality at the CHF location as long as the heated length is sufficiently long (e.g., the length-to-diameter (L/D) ratio is greater than 50) to remove any upstream history effects. Thus, for a given inside diameter, CHF becomes a function of the flow conditions at CHF (i.e., mass flux, pressure, and thermodynamic quality—the three parameters of the CHF LUT).

The following secondary parameters could affect the CHF:

- Test-Section Orientation. Although most CHF tests have been performed for upward flow in vertical test sections, some investigators have investigated the CHF behavior in horizontal flow and downflow (e.g., Wong et al., 1990). Based on an extensive analysis of CHF in horizontal tubes, Wong et al. (1990) has shown that the effects of a horizontal test-section orientation are not significant at high flow where flow stratification occurrence is suppressed. The boundaries of flow stratification can be estimated from flow regime maps, such as those proposed by Taitel and Dukler (1975).

- Test-Section Material. Test-section material, in general, has little effect on CHF during flow boiling. However, for low flows and conditions where CHF is the result of DNB, high-conducting test-section materials could suppress the occurrence of hot spots under bubbles and thus increase the CHF.

- Type of Heating. Most CHF experiments are performed on directly heated tubes (Joule heating), whereas the most typical application is indirect heating of a fuel sheath for which the heat source is nuclear heat. Leung et al. (1982) compared experimentally the CHF for direct and indirect heating and observed no significant effect.

- Wall Thickness. Several experimenters (e.g., Bergles, 1963; Bennett et al., 1965) investigated the wall thickness effect of CHF but found no discernible effect. Some effect could possibly be present for very thin walls that could limit the heat of hotspots during a DNB-type CHF.

- Surface Roughness. Most test sections had a very smooth surface finish (similar to a fuel sheath), and the impact of the very small surface roughness was not found to be significant. Even for cases with a machined surface roughness, the impact of roughness on CHF is generally small because the vapor generation rate at the surface usually determines the CHF occurrence. However, when the surface roughness becomes larger than the film thickness (in annular film dryout), premature film breakdown could reduce CHF.

- Inlet/Outlet Throttling. The majority of CHF experiments considered the flow free from fluctuations; however, restricting the flow at the outlet could cause an instability in flow and pressure and, therefore, could significantly reduce CHF, as observed by Lowdermilk (1958) and Mayinger et al. (1966). Kirillov (1997) also observed flow oscillations with a "soft" inlet (no throttling) as opposed to a "hard" inlet (with throttling) that generally suppressed the occurrence of flow oscillations.

- Dissolved Gas Content in the Coolant. Most CHF experiments used degassed water; however, some experiments have purposely used dissolved gas in the coolant to examine its effect on boiling heat transfer. Kirillov (1997) reported on Russian experiments in which reductions of up to 30 percent in CHF were observed for dissolved gas content of 4,000 normal cubic centimeters per kilogram.

2.4 Critical Heat Flux Reproducibility

In the late 1960s and 1970s, the concern was raised in Europe that significant differences in CHF could exist between measurements obtained at different heat transfer laboratories on nominally the same test section and for the same flow conditions. Therefore, two independent reproducibility exercises were performed, one in Western Europe in 1970 and one reported in the Union of Soviet Socialist Republics (U.S.S.R.) literature in 1984/1985. The objective of these reproducibility studies was to determine the variation in CHF measurements between various laboratories. About 8–10 laboratories participated in each of these two reproducibility studies. The sections titled, "CISE (1970)/Nilsson (1970) European CHF Reproducibility Exercise," and "Kirillov (1984, 1985) CHF Reproducibility Study," in Appendix I summarize these two reproducibility studies. In general, the agreement between the various European laboratories was within 10 percent except for two outliers that were later disqualified.

3 EVOLUTION OF CRITICAL HEAT FLUX PREDICTION METHODS

3.1 Empirical Critical Heat Flux Correlations

CHF prediction methods for flow boiling were reported as early as 1949 (McAdams, 1949). The interest in CHF initially grew slowly but expanded rapidly in the early 1960s as an improved knowledge of CHF was urgently needed to determine the power limits for the many reactors then under construction around the world. A book by Tong (1965) (the first book that covered flow boiling CHF) reviewed several of the early CHF prediction methods, most of which were purely empirical. In parallel, Clerici (1966) published a list of over 50 CHF correlations for water-cooled tubes. Since then, the number of published CHF correlations for water-cooled tubes has increased to well over 500. In contrast to pool boiling for which the early prediction methods are still in use, none of the early flow boiling CHF correlations for tubes carry much credibility today, partially because the pool boiling CHF equations had a physical basis, whereas the tube CHF correlations were virtually all empirical.

Most of the tube CHF correlations have essentially the form $CHF = f(P, G, X_{CHF}, D)$ or are in a dimensionless form $\frac{CHF}{H_{fg}G} = f\left(\frac{\rho_f}{\rho_g}, G\frac{D^{0.5}}{(\sigma\rho_f)^{0.5}}, X_{CHF}, \frac{D}{D_{ref}}\right)$, although other dimensionless parameters may have been used as well. The choice of correlation parameters (P, G, X_{CHF}, D) is essentially correct, but the functional relationship between these parameters varies with flow conditions—hence, the large proliferation of correlations. The CHF equations of Katto (1992) and Lee and Mudawar (1988) deserve special mention because they (1) have a phenomenological basis, (2) are based on a large database, and (3) appear to have a wider range of validity.

3.2 Analytical Critical Heat Flux Models

The lack of a satisfactory CHF prediction technique using empirical correlations led to the development of analytical CHF models, starting in the late 1960s. These models, which were based on the physical mechanisms and satisfy the conservation equations, can be divided into two main groups:

1) Annular Film Dryout Models. These models are based on a mass balance on the liquid film in annular flow and postulate that CHF corresponds to the depletion of the liquid film. Hewitt and co-workers (Hewitt and Hall-Taylor, 1970; Bennett et al., 1967) developed the original annular film dryout models in the 1960s. The models differ in the equations for droplet entrainment and deposition and interfacial friction and heat transfer. These models provide reasonable predictions of CHF for the annular flow at medium to high pressures and flows and void fractions exceeding 50 percent (Hewitt and Hall-Taylor, 1970).

2) Bubbly Layer Models. These models postulate that CHF occurs in the lower quality regime when the bubble layer covering the heated surface becomes so thick and saturated with bubbles that no liquid mixing between the near-wall layer and the cooler core liquid is possible. Tong (1965, 1968) and Tong and Hewitt (1972) proposed early versions of this model. This model and subsequent variations proposed by Weisman and Pei (1983) and Ying and Weisman (1986) appear to predict the CHF with reasonable accuracy under high-pressure, high-flow, and low-quality or subcooled conditions.

Although the analytical models have improved significantly and usually predict the correct asymptotic trends after suitable fine tuning, the evaluation process is complex and time consuming. In the 1970s and 1980s, developing CHF models was a popular academic pursuit and resulted in the more than 50 CHF models now available, each based on different assumptions of interfacial relationships. CHF models tend to be less accurate than empirical correlations over the range of the correlation's database. Weisman (1992) presented an excellent review of the analytical CHF models.

3.3 Critical Heat Flux Lookup Table Methods

Because of the proliferation in CHF correlations and models and the limited range of application of the models and correlations, the need for a more generalized CHF prediction technique is obvious. As a basis of the generalized technique, the common "local conditions hypothesis" was used (i.e., the assumption was that the CHF for a water-cooled tube and a fixed tube diameter is a unique function of local pressure (P), mass flux (G), and thermodynamic quality (X)). Doroshchuk et al. (1975) made an initial attempt to construct a standard table of CHF values for a given geometry using a limited database of 5,000 data points for water-cooled tubes. This table and all subsequent tables contain normalized CHF values for a vertical 8-millimeter (mm) water-cooled tube for various pressures, mass fluxes, and qualities. The Center for Nuclear Studies in Grenoble (France), the University of Ottawa (Canada), the Institute of Physics and Power Engineering (IPPE) (U.S.S.R.), and Atomic Energy of Canada Limited (AECL) (Canada) subsequently improved and expanded the CHF LUT using an ever-increasing CHF database.

In 1986, Groeneveld et al. published the "AECL-UO" table, which covers a much wider range of conditions than Doroshchuk's table. The databank on which the 1986 LUT was based contained 15,442 CHF data points taken from 12 separate data sets and the two data compilations of Thompson and MacBeth (1964) and Zenkevich (1974). Kirillov et al. (1989a, 1989b, 1991a, 1991b) improved the CHF table of Doroshchuk et al. by introducing a larger database, but the range of applications covered in their tables remained smaller than that of the AECL-UO table. Groeneveld and Kirillov used different databases and methodologies to derive their respective tables. A subsequent data exchange agreement between Groeneveld and Kirillov resulted in a combined CHF databank of more than 30,000 tube CHF data points (24,000 data points after removing duplicates), which was used to derive the 1995 CHF LUT. The 1995 CHF LUT has a wider range of validity and presents normalized CHF values for 21 pressures, 20 mass fluxes, and 23 critical qualities covering, respectively, ranges of 0.1 to 20 megapascals (MPa), 0 to 8 megagrams per square meter per second (zero flow refers to pool-boiling conditions), and -50 to 100 percent (negative qualities refer to subcooled conditions). The 1995 LUT also removed the sharp variations in CHF that were present at some of the boundaries between regions where experimental data were available and regions where correlations and extrapolations were used. A smoothing procedure developed by Huang and Cheng (1994), as described in Section 5.3 , was used to suppress these sharp variations.

Between 1995 and 2006, 27 additional CHF data sets for vertical tubes with upward water flow that were not used for the development of the 1996 CHF LUT were acquired. Further enhancements were made to the CHF LUT and its database by AECL and the University of Ottawa, culminating in the 2006 CHF LUT as described in the *Nuclear Engineering and Design* article by Groeneveld et al. (2007) titled, "The 2006 CHF Look-Up Table." Appendix II-1 lists the CHF data sets used for developing the 2006 CHF LUT. Note that the space requirements of the

Nuclear Engineering and Design journal did not permit the inclusion of the complete CHF LUT; instead, the journal article presented a somewhat condensed version. Appendix III presents the complete CHF LUT.

The most recent CHF LUT method (Groeneveld et al., 2007) provides CHF values for water-cooled tubes at discrete values of pressure (P), mass flux (G), and thermodynamic quality (X), covering respectively the ranges of 0.1 to 20 MPa, 0 to 7,500 kilograms per square meter per second (kg m^{-2} s^{-1}) (zero flow refers to pool-boiling conditions), and -50 to 100 percent (negative qualities refer to subcooled conditions). Linear interpolation between table values is used for determining CHF at in-between table conditions. Extrapolation is usually not necessary because the table covers a very wide range of conditions. Compared to other available prediction methods, the tabular approach has the following advantages:

- The approach has greater accuracy.
- It has a wider range of applicability.
- It can predict the correct asymptotic trend(s).
- It requires less computing time.
- It can be easily updated if additional data become available.

Section 5.0 summarizes the derivation of the LUT. Since the derivation of the 2006 CHF LUT, additional data sets have become available. Sections II-2 and II-3 of Appendix II provide references to these additional data sets. These additional data sets can be used to update the CHF LUT or to independently validate the CHF LUT.

4 DATABASE FOR THE 2006 CRITICAL HEAT FLUX LOOKUP TABLE

4.1 Critical Heat Flux Data Compilations

DeBortoli (as reported by Firstenberg et al. (1960)) created the first CHF data compilation for tube data. Subsequently, many CHF data compilations have been assembled, either for tube CHF data or for tube and more complex geometries (e.g., annuli or bundles). Seventeen CHF data compilations for tubes were identified; Section II-4 of Appendix II includes references to these data sets.

Many of these compilations give sources for the CHF data used to derive the CHF LUTs. To eliminate possible errors in transcribing data, we always attempted to locate the original source of the data instead of relying on the (sometimes questionable) accuracy of the CHF compilations done by others.

Two of the compilations (European Reproducibility Study 1970 and U.S.S.R. Reproducibility Study 1984) represent the results of two separate CHF reproducibility studies. Eight to 10 laboratories participated in each of these two reproducibility studies. The Appendix I sections titled, "Kirillov (1984, 1985) CHF Reproducibility Study," and "CISE (1970)/Nilsson (1970) European CHF Reproducibility Exercise," summarize these two reproducibility studies.

4.2 Electronic Database of Data Used To Derive the 2006 Critical Heat Flux Lookup Table

The 25,000 experimental data points used to derive the 2016 CHF LUT were tabulated in an electronic database (Compact Disc (CD) Spreadsheet "CHF Data for 2006 LUT.xls"). The first page of this database (Table 4-1) provides an overview of the flow parameters for each CHF point. Section 4.3 summarizes each data set.

Table 4-2 summarizes the range of conditions of each processed CHF data set and includes supplementary data that have been processed subsequent to the 2006 CHF LUT derivation with the data set name presented in italics. Section II-2 of Appendix II provides the references to these data sets. In addition, Section II-3 of Appendix II contains references to additional data sets that have not yet been processed.

Table 4-1 Sample Page from the CHF Database (CD Spreadsheet "CHF Data for 2006 LUT.xls")

Data	D	L	P	G	X_{chf}	DH_{in}	CHF	Tin	Reference
—	m	m	kPa	kg $m^{-2}s^{-1}$	—	kJ/kg	kW m^{-2}	°C	
25	0.004	0.396	100	77.5	0.84	317	442	23.94	Lowdermilk, 1958
26	0.004	0.396	100	142.7	0.79	317	757	23.94	Lowdermilk, 1958
27	0.004	0.396	100	203.9	0.7	317	978	23.94	Lowdermilk, 1958
28	0.004	0.396	100	271.8	0.73	317	1,325	23.94	Lowdermilk, 1958
29	0.004	0.396	100	421.3	0.62	317	1,798	23.94	Lowdermilk, 1958
30	0.004	0.396	100	543.6	0.58	317	2,239	23.94	Lowdermilk, 1958
31	0.004	0.396	100	679.5	0.55	317	2,712	23.94	Lowdermilk, 1958
32	0.004	0.396	100	978.5	0.5	317	3,564	23.94	Lowdermilk, 1958
33	0.004	0.396	100	1,372.7	0.45	317	4,573	23.94	Lowdermilk, 1958
34	0.004	0.396	100	1,644.5	0.42	317	5,236	23.94	Lowdermilk, 1958
35	0.004	0.594	100	77.5	0.88	324	300	22.27	Lowdermilk, 1958
36	0.004	0.594	100	135.9	0.81	324	505	22.27	Lowdermilk, 1958
37	0.004	0.594	100	203.9	0.75	324	694	22.27	Lowdermilk, 1958
38	0.004	0.594	100	258.2	0.71	331	852	20.6	Lowdermilk, 1958
39	0.004	0.594	100	407.7	0.63	331	1,199	20.6	Lowdermilk, 1958
40	0.004	0.594	100	543.6	0.6	331	1,514	20.6	Lowdermilk, 1958
41	0.004	0.594	100	693.1	0.58	331	1,892	20.6	Lowdermilk, 1958
42	0.004	0.594	100	992.1	0.56	331	2,618	20.6	Lowdermilk, 1958
43	0.004	0.792	100	78.8	0.74	331	196	20.6	Lowdermilk, 1958
44	0.004	0.792	100	135.9	0.76	331	347	20.6	Lowdermilk, 1958
45	0.004	0.792	100	217.5	0.72	331	536	20.6	Lowdermilk, 1958

Table 4-2 Ranges of Conditions of Processed CHF Data Sets

Source of CHF Data	Number of Data Points	Tube Diameter	Heating Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
Reference	number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
Alekseev (1964) data from Kirillov (1992)	70	10.00 10.01	1.000 4.966	9,800 19,610	216 7,566	-0.866 0.944	57 1,398	134 4,949	139.77 357.93
Alessandrini et al. (1963)	753	15.2 24.9	0.80 2.46	4,795 5,148	1,080 4,140	-0.04 0.75	-1,110 365	206 3,689	185 265
Babarin et al. (1969)	163	12.0	0.96 1.80	284 310	50 500	0.466 1.091	37.6 495	190 2,300	15 124
Babcock and Hood (1962)	39	8.00 22.5	0.61	413 6,890	2,946 11,452	-0.187 -0.05	202 639	4,876 10,546	19 177
Baek (2001)	56	6.00 10.0	0.18 0.40	101 3,618	497 2,032	-0.091 0.099	254 935	2,041 7,413	5.9 40.2
Bailey (1977)	110	15.0	3.77 5.37	1,350 7,080	49 1,383	0.45 0.99	-178 473	84 1,134	93 286
Bailey and Lee (1969)	158	9.30	3.05	6,895 18,340	958 4,242	0.069 0.727	54 604	344 2,221	199 347
Becker et al. (1963) AE-114	2,659	3.94 20.10	0.100 3.750	216 8,973	100 3,183	-0.069 1.054	-50 1,640	278 7,477	25.42
Becker (1965) AE-RTL-778	1,326	3.93 37.47	0.216 3.750	1,128 9,905	159.5 5,586	-0.005 0.993	-16 2,711	503 6,620	63.32 288.71
Becker (1970) TPM-RL-1260	116	2.40 36.03	0.500 1.880	3,050 7,100	93.3 2,725	0.207 0.903	371 1,065	1,026 5,130	51.75 113.22
Becker et al. (1971) KTH-NEL-14	1,455	10.00 10.01	1.000 4.966	3,000 20,000	156 8,111	-0.866 1.061	26 1,414	135 5,476	124.75 358.65

Source of CHF Data	**Number of Data Points**	**Tube Diameter**	**Heating Length**	**Pressure**	**Mass Flux**	**Critical Quality**	**Inlet Subcooling**	**Heat Flux**	**Inlet Temperature**
Reference	number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
Bennett et al. (1965) AERE-R 5055	201	9.22 12.62	1.524 5.563	6,612 7,481	623.8 5,844.4	0.026 0.948	21 691	589.6 3,299.7	157.67 279.45
Bergelson (1980) data from Kirillov (1992)	328	8.00	0.241 0.400	170 3,080	1,927 7,078	-0.295 0.090	96 853	3,511 14,571	28.94 169.20
Bergles (1963) ASME 63-WA-182	117	0.62 6.21	0.011 0.155	140 586	1,518.7 24,272.4	-0.137 0.111	25 534	4,957.1 44,713	3.10 116.55
Bertoletti et al. (1964)	*386*	*4.90* *15.20*	*0.050* *2.675*	*4,881* *9,876*	*1,051* *3,948.8*	*-0.083* *0.774*	*-28* *769*	*198.7* *7,502.8*	*112.97* *302.14*
Biancone et al. (1965)	*245*	*10.2* *17.1*	*0.78* *1.32*	*7,914* *14,396*	*465* *3,167*	*-0.25* *0.662*	*45* *1,355*	*742* *6,649*	*48* *326*
Borodin and Macdonald (1983) CRNL-2538	*Restricted distribution*								
Burck and Hufschmidt (1965)	143	10.0	0.35	1,100 3,090	917 3,756	-0.246 0.087	532 939	4,500 12,200	16.7 60.8
Campolunghi (1973)	*218*	*12.0*	*15.6* *20.5*	*254* *9,660*	*1,111* *2,545*	*0.296* *0.772*	*19.6* *740*	*155* *479*	*205* *260*
Celata et al. (1992a) set 1	60	6.00 8.00	0.10 0.15	398 5,120	2,019 10,046	-0.517 -0.106	350 1,018	7,428 29,514	29 81
Celata et al. (1992b) set 2	78	2.50 5.00	0.20 0.40	107 2,181	2,166 32,637	-0.091 0.287	345 790	5,347 42,777	19 55
Celata and Mariani (1993)	88	0.10 22.50	0.002 0.610	90 6,890	917 90,000	0.007 0.923	88 1,023	4,000 228,000	3.44 245.78

Source of CHF Data	**Number of Data Points**	**Tube Diameter**	**Heating Length**	**Pressure**	**Mass Flux**	**Critical Quality**	**Inlet Subcooling**	**Heat Flux**	**Inlet Temperature**
Reference	number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
Celata et al. (1993)	78	2.50	0.10	578 2,714	11,240 40,000	-0.357 -0.104	387 844	12,113 60,579	30 70.5
Cheng et al. (1983a)	150	12.60	0.370 0.740	101 687	50 400	0.187 1.227	42 210	331.2 2,115	70.00 154.61
Cheng et al. (1983b)	132	4.80	0.19 0.38	100 700	300 750	0.082 0.765	42 214	889 2,131	49.6 145
Dell et al. (1969) AERE-M 2216	82	6.17	0.914 5.512	6,895	14,328.9 4,135.8	0.144 0.779	79 365	492.7 3,340.4	217.13 270.09
Doerffer (1999)	*Proprietary data*								
Doerffer et al. (1997)	*Proprietary data*								
Era et al. (1966)	163	5.98	1.602 4.800	6,777 7,049	1,105 3,014.9	0.374 0.952	-1,211 565	109.2 1,960.9	181.13 509.30
Griffel (1965) NYO-187-7	397	6.22 37.46	0.610 1.972	3,448 10,343	637.3 18,577.2	-0.209 0.592	45 1,209	1,400.6 8,107.3	87.68 287.07
Groeneveld (1985)	*Proprietary data*								
Hassid et al. (1967) *CISE-R-236*	*191*	*24.90* *25.10*	*1.590* *2.391*	*2,942* *6,090*	*369.3* *3,857.5*	*-0.035* *0.838*	*1,427* *3,433*	*1,430.9* *3,444.1*	*153.89* *267.66*
Hewitt et al. (1965) AERE-R 4864.	442	9.30	0.229 3.048	101 208	90.9 301	0.160 1.083	-41 383	144 4,013	13.71 119.39
Hood (1962)	61	6.30 25.4	0.61	414 8,412	2,156 11,390	-0.25 -0.05	204 1,113	5,741 11,830	-20 243

Source of CHF Data	Number of Data Points	Tube Diameter	Heating Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
Reference	number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
Hood and Isakoff (1962)	24	8.00 22.2	0.60 1.10	6,895	664 2,726	0.001 0.484	66 1,224	3,186 4,637	7.5 272
Inasaka et al. (1991)	*8*	*6.00*	*0.10*	*104* *114*	*6,520* *11,364*	*-0.09* *-0.07*	*250* *266*	*7,280* *11,200*	*39* *41*
Inasaka and Nariai (1989)	29	3.00	0.10	290 1,050	4,300 29,900	-0.188 -0.051	266 626	7,300 44,500	25 78
Jafri (1993)	49	15.8	2.44	317 1,060	1,439 8,102	-0.021 0.28	223 667	1,795 5,691	19 129
Jens and Lottes (1951) Subcooling CHF data	48	5.74	0.625	3,448 13,790	1,301.8 10,603.9	-0.464 -0.015	279 1,310	2,965.3 11,924.4	70.52 285.05
Judd and Wilson (1966) BAW-3238-9	49	11.30	1.829	6,861 13,859	673.9 3,428	0.016 0.776	33 730	593.1 2,668.8	207.11 323.84
Kim et al. (2000)	502	6.00 12.0	0.30 1.77	104 951	21 277	0.397 1.251	0.8 634	130 1,598	20 156
Kirillov et al. (1984)	2,470	7.71 8.09	0.990 6.000	6,370 18,040	494 4,154	-0.494 0.981	7 1,537	110 7,700	79.41 350.90
Kureta (1997)	913	1.00 6.00	0.04 0.68	101.3	4.1 19,130	-0.147 1.664	0 391	185 158,100	6.7 100
Ladislau (1978) (see Kirillov database (1992))	136	4.00	0.200	420 1,000	884 5,504	-0.051 -0.009	104 638	1,860 4,631	28.04 149.56
Lee (1965)	38	9.50	1.73 3.05	6,828 7,024	2,020 5,720	0.002 0.433	75.5 577	1,307 3,873	161 271

Source of CHF Data	Number of Data Points	Tube Diameter	Heating Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
Reference	number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
Lee (1966) AEEW-R479	435	14.10 44.70	0.635 1.524	8,237 12,579	332.2 3,410.3	-0.110 0.780	60 451	870.7 3,738.2	259.80 318.09
Leung et al. (1989)	66	5.45	2.511	5,030 9,710	1,167.6 9,938.3	0.210 0.578	6 316	656.2 3,058.3	227.85 305.33
Leung et al. (1990)	*Restricted distribution*								
Lowdermilk et al. (1958)	470	4.00 4.80	0.119 0.991	100	27.2 4,865.5	0.030 1.236	317 331	167 9,525	20.91 24.24
Matzner et al. (1965)	99	10.20	2.438 4.877	6,893	1,193.3 9,559.8	0.008 0.693	48 1,183	643.5 4,041	65.61 275.82
Mayinger et al. (1966)	128	7.00	0.560 0.980	1,925 10,244	2,233 3,734	0.098 0.405	-239 314	924 5,618	233.28 310.09
Mudawar and Bowers (1999)	*174*	*0.40* *2.50*	*0.004* *0.031*	*250* *17,240*	*5,000* *134,000*	*-1.778* *-0.062*	*254* *1,579*	*9,400* *276,000*	*18* *70*
Nariai et al. (1987)	93	1.00 3.00	0.009 0.101	100	6,710 20,910	-0.134 0.007	149.5 353	4647 69,990	15.4 64
Nariai et al. (1991)	*7*	*6.00*	*0.10*	*196* *1,470*	*7,700* *9,952*	*-0.24* *-0.096*	*306* *618*	*12,110* *17,230*	*33* *53*
Nariai CHF data set from Celata (2001)	14	6.0	0.100	100 1,500	4,590 8,690	-0.2595 0.0577	31 281	8,500 22,100	38.3 44.7
Nguyen and Yin (1975)	56	12.60	2.438 4.877	6,645 8,401	929.6 3,838.4	0.216 0.738	52 413	677 2,023.7	225.06 276.81
Olekhnovitch (1997)	479	8.00	0.75 3.50	507 4,036	977 6,122	0.046 0.761	4 498	523 5,550	47 244

Source of CHF Data	Number of Data Points	Tube Diameter	Heating Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
Reference	number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
Ornatskii (1963)	*69*	*2.00*	*0.04*	*17,732* *20,265*	*5,000* *30,000*	*-2.41* *-0.054*	*175* *1,811*	*5,579* *70,314*	*-21* *335*
Ornatskii and Kichigin (1961)	*222*	*2.00*	*0.04*	*1,013* *7,599*	*5,000* *30,000*	*-0.654* *-0.002*	*72* *1,176*	*6,392* *70,895*	*2.25* *263.8*
Ornatskii and Kichigin (1962)	*169*	*2.00*	*0.04*	*7,599* *15,199*	*5000* *30000*	*-1.23* *-0.026*	*79* *1,566*	*8,136* *72,058*	*0.88* *331*
Ornatskii and Viniarskii (1965)	*109*	*0.50*	*0.014*	*1,013* *7,194*	*20,000* *90,000*	*-0.572* *-0.107*	*321* *1,942*	*39,542* *224,459*	*-20* *195*
Pabisz and Bergles (1996)	10	4.40 6.20	0.11 0.154	627 1,284	2,417 4,994	-0.196 -0.133	567 698	7,370 13,880	15.3 46
Peterlongo et al. (1964)	349	15.1 15.2	1.62 4.02	4933 6,551	1,010 4,020	-0.02 0.608	-90 1,038	895 4,115	27 281
Ruan (1994)	*41*	*9.00*	*0.40*	*106* *707*	*12* *207*	*0.469* *0.966*	*15* *279*	*139.4* *1,955*	*40* *153*
Rudzinski (1999) MR1-A Data (Private Communication)	*Restricted distribution*								
Shan (2005)	24	8.00	1.00	13,337 14,808	572 4,137	-0.022 0.422	97 692	819.5 4,511	198 328
Shlykov et al. (1970)	*60*	*3.60*	*0.10*	*76.5* *386*	*12,865* *25,494*	*-0.167* *-0.022*	*149* *508*	*12,800* *30,300*	*3* *98*
Smolin et al. (1962)	369	3.84 10.80	0.776 4.000	7,840 19,610	498 7,556	-0.132 0.795	5 1,329	230 5,652	140.35 350.39

Source of CHF Data	**Number of Data Points**	**Tube Diameter**	**Heating Length**	**Pressure**	**Mass Flux**	**Critical Quality**	**Inlet Subcooling**	**Heat Flux**	**Inlet Temperature**
Reference	number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
Smolin et al. (1979) data from Kirillov (1992)	2,987	3.84 16.00	0.690 6.050	2,940 17,710	490 7,672	-0.136 0.789	4 1,362	245 5,626	72.72 351.65
Snoek (1988) (CRNL-4231)	*Proprietary data*								
Soderquist (1994)	1,463	8.00 8.10	1.00 6.00	970 20,120	243 6,086	-0.169 1.336	35 693	94 3,879	112 355
Stein (2004)	*383*	*9.00*	*0.13* *0.45*	*1,090* *7,140*	*24* *304.5*	*-0.002* *1*	*215* *1,245*	*237.5* *4,700.5*	*134* *272*
Swenson et al. (1962)	25	10.4 10.5	1.75 1.80	13,790	679 1,765	0.178 0.502	44 564	587 1,063	231 329
Tain (1994)	55	8.00	1.75	6,849 10,127	2,401 7,832	0.028 0.378	27 455	1,341 4,358	191 299
Tong (1964)	266	6.22 12.90	0.380 3.660	5,171 13,790	678 14,002	0.002 0.502	5 1,060	587 6,139	263.94 330.85
Vandervort (1992)	*210*	*0.30* *2.70*	*0.002* *0.066*	*131* *2,277*	*8,438* *41,810*	*-0.276* *-0.018*	*169* *759*	*18,700* *123,800*	*6.4* *85*
Waters et al. (1965)	37	11.2	0.61 3.65	6,895 10,342	6,578 9,548	-0.033 0.322	-322 1,050	2,017 5,389	87 313
Weber and Johannsen (1990)	*55*	*9.70*	*0.043*	*110* *1,200*	*10.8* *301*	*0.072* *1.53*	*4.2* *577*	*1,495* *7,572*	*65* *175*
Whittle and Forgan (1967)	59	6.45	0.4064 0.6096	117.2 172.4	1,643.5 9,137	-0.0311 -0.0088	290 171	660 3,480	35 75

Source of CHF Data	Number of Data Points	Tube Diameter	Heating Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
Reference	number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
Williams and Baus (1980)	129	9.50	1.84	2,758 15,169	324 4,663	-0.025 0.929	140 1,223	388 4,073	90 315
Yildiz (1997)	*385*	*6.00* *8.00*	*0.17* *0.31*	*90* *721*	*48.5* *411*	*0.001* *0.914*	*-4.26* *1,057*	*533* *4,381*	*31* *158*
Yin et al. (1988)	287	13.40	3.658	1,028 21,197	1,938.9 2,081.6	0.075 0.431	0 493	583.3 1,863.7	128.42 358.41
Zenkevich (1969) data from Kirillov (1992)	5,595	3.99 15.10	0.250 6.000	5,880 19,610	498 9,876	-1.652 0.964	2 1,644	136 14,760	76.01 361.79
Zenkevich (1971) data from Kirillov (1992)	392	7.80 8.05	7.000 20.000	6,860 17,650	1,008 2,783	0.262 0.876	18 1,549	47 1,283	81.96 352.22
Zenkevich et al. (1974) data different from the others	823	4.80 12.60	1.000 6.000	5,890 19,620	497.2 6,694.4	-0.221 0.969	5 1,381	230 4,740	96.70 358.24
Zenkevich et al. (1964)	63	6.8 10.0	0.10 0.39	3,924 9,810	550 6,444	-0.02 0.693	131 279	4,910 9,710	211 286

4.3 <u>Description of the Experimental Data Sets</u>

Appendix I summarizes the pertinent experimental details of the many data sets used to derive the 2006 CHF LUT. This appendix generally specifies the method of CHF detection. If a method is not specified, CHF detection by thermocouples is the most likely method.

5 DERIVATION OF THE 2006 CRITICAL HEAT FLUX LOOKUP TABLE

5.1 Critical Heat Flux Data Selection Criteria

Not all CHF data points were used for the derivation of the CHF LUTs. The CHF data selection criteria used for screening the CHF database have evolved from the relatively simple check for duplicates and heat balance inconsistencies used during the 1986 CHF LUT derivation to the more sophisticated approach used in the 2006 CHF LUT derivation process. The most recent CHF data selection criteria are as follows:

- acceptable values for diameter ($3 < D < 25$ mm), L/D ratio ($L/D > 50$ for $X_{cr} > 0$, $L/D > 25$ for $X_{cr} < 0$), pressure ($100 \leq P \leq 21,000$ kilopascal (kPa)), mass flux ($0 \leq G < 8,000$ kg m^{-2} s^{-1}), and quality ($X_{cr} < 1.0$)

- data that must satisfy the heat balance (i.e., reported power should be approximately equal to [flow]*[enthalpy rise])

- identification of outliers using the slice method (Durmayaz et al., 2004)

    - The "slice" method was introduced to examine all the data behind each set of flow conditions in the LUT. For each nominal LUT pressure slice, $\frac{(P_{i-1}+P_i)}{2} < P < \frac{(P_{i+1}+P_i)}{2}$, and for each nominal mass flux, $\frac{(G_{j-1}+G_j)}{2} < G < \frac{(G_{j+1}+G_j)}{2}$, a CHF versus critical quality plot was created. Data that did not obviously agree with the bulk of the data and the previous CHF LUT were labeled as "outliers" and were excluded in the CHF LUT derivation process. A similar slice approach was used for the CHF versus pressure (P) and CHF versus mass flux (G) plots.

- identification of duplicate data using the slice method (i.e., more than one author may have reported the same data sets)

- removal of data sets that display a significant scatter and generally disagree with the bulk of the data

    - These "bad" data sets may result from "soft" inlet conditions that can give rise to flow instabilities or a poorly performed experiment (e.g., large uncertainties in instrumentation).

5.2 Derivation of the Skeleton Table

The derivation of the CHF LUT requires a skeleton table to provide the initial estimate of the CHF LUT values. The skeleton CHF values are used for evaluating the slopes of CHF versus P, G, or X. The slopes are used for extrapolating selected CHF measurements to the surrounding LUT values of pressure (P), mass flux (G), and thermodynamic quality (X) as described by Groeneveld et al. (1996). The skeleton table also provides the default CHF values under conditions where no experimental data are available.

The skeleton table is primarily based on the 1995 CHF LUT but with corrections to the subcooled region. These corrections were necessary because the skeleton table for the 1995 CHF LUT was partially based on the Katto (1992) equation, which was subsequently found to contain discontinuities or trend reversals at certain conditions.

Values in the skeleton table for G = 0 kg m^{-2} s^{-1} and X < 0 are predicted using the Zuber (1959) correlation with the correction factor derived by Ivey and Morris (1962). The skeleton table values for G > 300 kg m^{-2} s^{-1} and X < 0 are either maintained or replaced with the predicted values by the Hall and Mudawar (2000) equation, based on a visual observation of the plots produced by slicing the LUT and the data trends.

Generally, for 0 < G < 300 kg m^{-2} s^{-1} and X < 0, the skeleton table values are established using a linear interpolation between those at zero flow and 500 kg m^{-2} s^{-1} to provide a smooth transition.

Compared to the 1995 LUT, three additional pressures (2, 4, and 21 MPa) and one mass flux (750 kg m^{-2} s^{-1}) were added to the 2006 LUT. The skeleton CHF values for conditions involving pressures at 2 and 4 MPa and a mass flux of 750 kg m^{-2} s^{-1} were obtained from linear interpolation. The skeleton table CHF values for 21 MPa were interpolated using the CHF versus pressure trend of the Zuber pool-boiling CHF equation, which was found to approximately agree with CHF versus pressure trends for flow boiling at very high pressures.

5.3 Derivation of the 2006 Critical Heat Flux Lookup Table

The primary building blocks for the CHF LUT are the screened database and the skeleton table. The steps described below were taken during the LUT derivation process.

The 1995 CHF LUT, which was modified as described in the previous section, was used as the skeleton table. The effect of tube diameter on CHF is accounted for by using the diameter correction factor, $\frac{CHF_D}{CHF_{D=8mm}} = \left(\frac{D}{8}\right)^{-0.5}$, for the range of 3 < D < 25 mm. Outside this range, the diameter effect appears to be absent (Wong, 1994).

For each set of LUT conditions (each combination of P_x, G_y, and X_z), all experimental data falling within the range $P_{x-1} < P_{exp} < P_{x+1}$, $G_{y-1} < G_{exp} < G_{y+1}$, and $X_{z-1} < X_{exp} < X_{z+1}$ were selected. Each experimental CHF point was corrected for the differences in pressure ($P_{exp} - P_x$), mass flux ($G_{exp} - G_y$), and quality ($X_{exp} - X_z$), using the slopes of the skeleton table and given an appropriate weight as described by Groeneveld et al. (1986, 2007). The weighted, averaged CHF value for all corrected data surrounding each table entry was used to replace the skeleton CHF value.

The updated CHF LUT is not smooth and displays an irregular variation (without any physical basis) in the three parametric ranges: pressure (P), mass flux (G), and quality (X). These fluctuations are attributed to data scatter, systematic differences between different data sets, and possible effects of second-order parameters such as heated length, surface conditions, and flow instability. Sharp variations in CHF were also observed at some of the boundaries between regions where experimental data are available and regions where correlations and extrapolations were used. Before finalizing the LUT, a smoothing procedure developed by Huang and Cheng (1994) was applied. The principle of the smoothing method is to fit three polynomials to six table entries in each parametric direction. The three polynomials intersect each other at the table entry, where the CHF value is then adjusted. This method significantly improved the smoothness of the LUT. A third-order polynomial was initially used for the

smoothing of the 1995 CHF LUT. However, the 2006 analysis showed that a first-order polynomial results in a smoother table with no significant loss in prediction accuracy.

Applying the smoothing process to the table entries under all conditions suppressed the discontinuity at the boundaries of the limiting quality region (LQR), as described by Groeneveld et al. (2007), resulting in a nonrepresentative trend to the experimental data. To maintain the physical trend of the table entries at the LQR, an intermediate table was created that maintained the more abrupt changes at the boundaries of the LQR, extrapolated to the nearest LUT qualities. Some smoothing was subsequently needed to avoid a fluctuation in CHF with pressure and mass flux.

6 DISCUSSION

6.1 Critical Heat Flux Data Coverage

The tabulation of experimental CHF data is based on the primary CHF parameters (i.e., those parameters used in correlating the CHF, such as pressure (P), mass flux (G), quality at CHF (X_{CHF}), and diameter (D). Because the quality at CHF is a calculated parameter, it is sometimes replaced with heated length (L) and inlet subcooling (ΔH_{in}) or inlet temperature. Figures 6-1 through 6-4 show the primary conditions for which water CHF data were available at the time of the 2006 CHF LUT derivation. These figures show CHF data coverage on L/D versus D, mass flux (G) versus pressure (P), quality (X) versus pressure (P), and quality (X) versus mass flux (G) maps, respectively. Superimposed on this are the supplementary data taken from 27 references processed after the 2006 CHF LUT. Appendix II-2 provides the references to these data sets.[1] Note that the supplementary data fill in some, but not all, gaps in the data. Despite the large database (over 40,000 data points), noticeable gaps still exist in flow conditions and geometry where CHF data are not available. The primary conditions for which data are scarce or missing include (1) high flows and high qualities, (2) low flows and low qualities, and (3) pressure ranges of 0.2 to 0.5 MPa. The reasons for the scarcity of CHF data under the above conditions are as follows:

- High Flow/High Quality. Obtaining CHF data at high flows and high qualities is very difficult because it requires the use of a complex two-phase inlet setup. Additional heat balance calculations across a preheater or mixer are necessary to obtain the test-section inlet enthalpy and inlet quality. The method used to introduce the two-phase mixture into the test section can also affect the CHF. Using a very long test section would be an alternative approach, but it is complex and expensive and would result in a very large pressure drop. Note that, at low pressures and high flows, this has occasionally resulted in critical flow conditions, which provide an upper flow limit (Tain, 1995).

- Low Flow/Subcooled CHF. At low pressures, negative qualities of less than -0.20 are impossible to obtain because they would result in water temperatures less than 0 degrees Celsius (C). In addition, the CHF is very high under these conditions, and this would result in a very large axial quality gradient (dX/dZ) (i.e., obtaining low-flow/low-quality CHF data would require very short test sections, whereby the entrance effects could affect the CHF). In addition, at highly subcooled conditions, the CHF can occur so fast that, in some tests, each CHF occurrence resulted in a physical test-section failure because of burnout.

- Low Pressures. Experiments at low pressure, especially for higher qualities and lower flow, could cause flow instability and, therefore, could lower the CHF.

Another possible reason for the scarcity in data for some of these conditions is lack of interest since heat transfer equipment may not operate under these conditions.

[1] Appendix II also contains references to additional data sets that have not yet been processed and, therefore, are not shown in Figures 6-1 through 6-4.

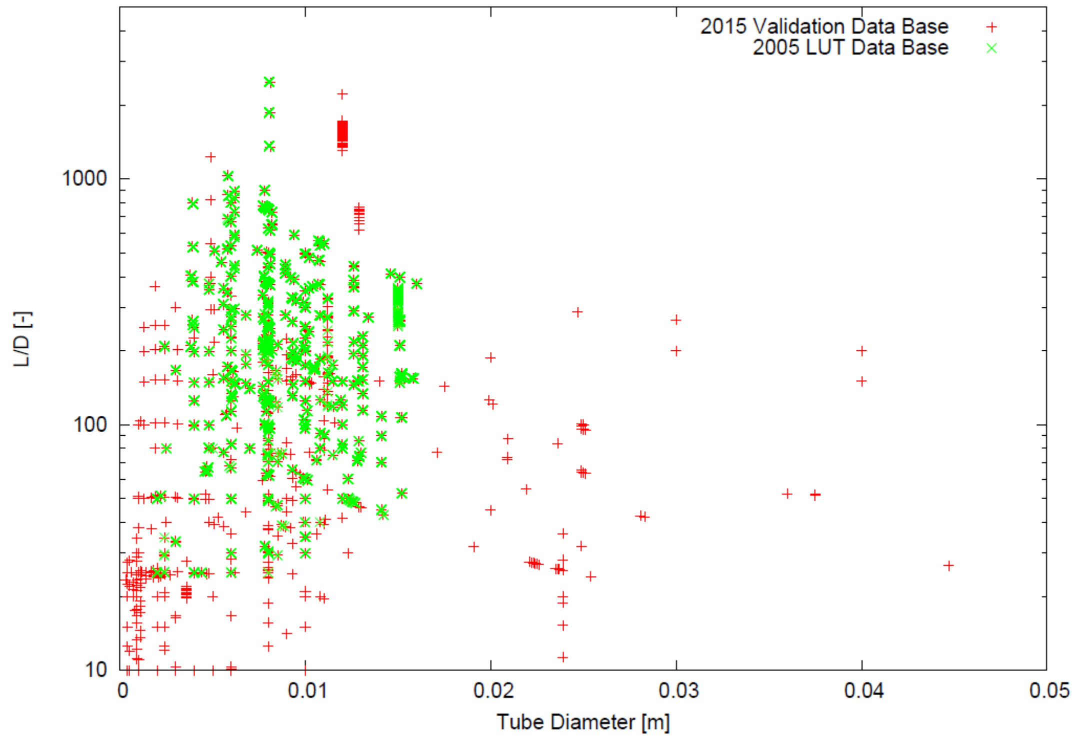

Figure 6-1 CHF Data Coverage on an L/D Versus D Map

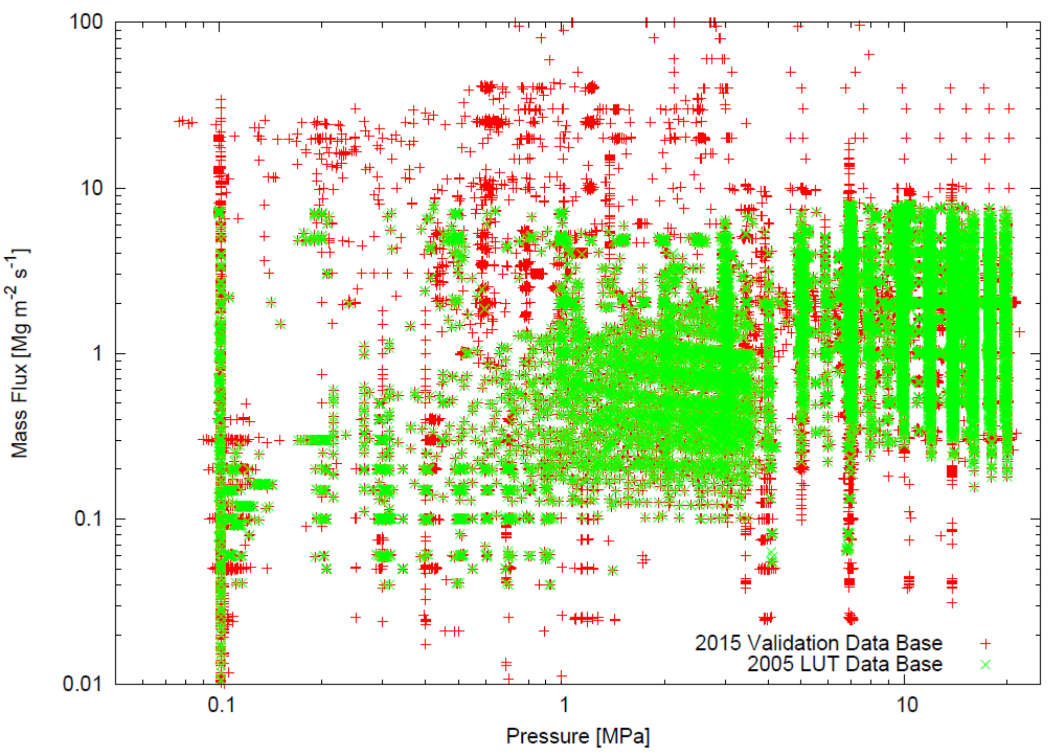

Figure 6-2 CHF Data Coverage on a Mass Flux Versus Pressure Map

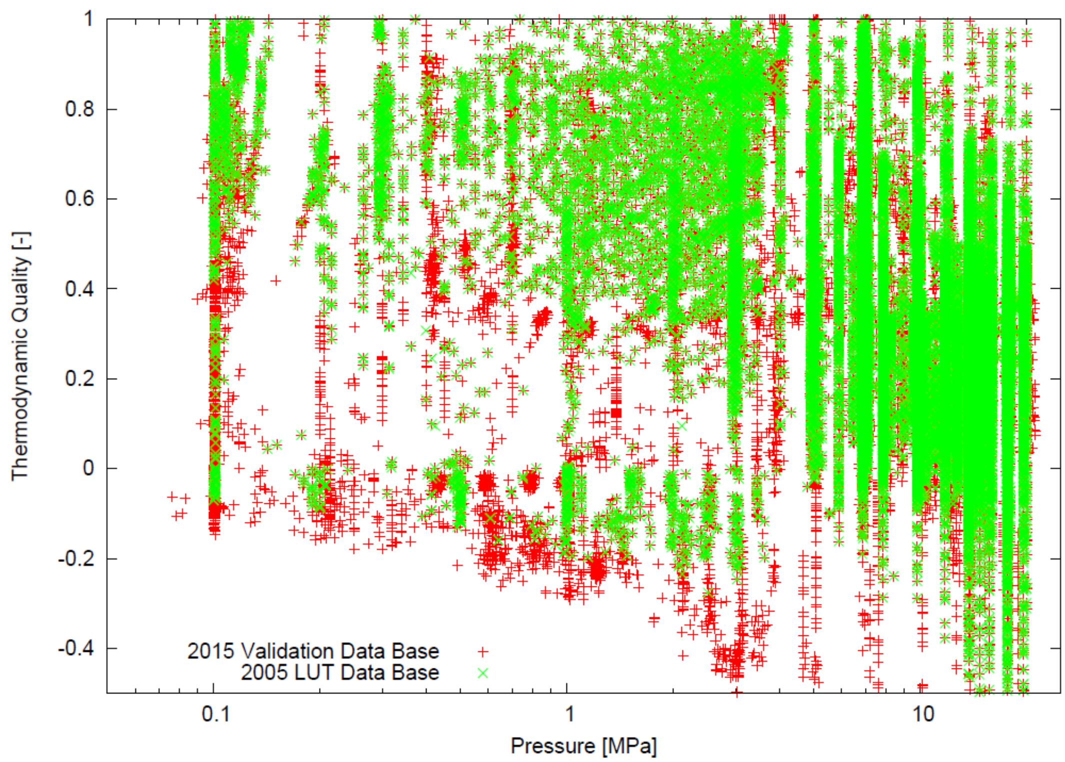

Figure 6-3 CHF Data Coverage on a Quality Versus Pressure Map

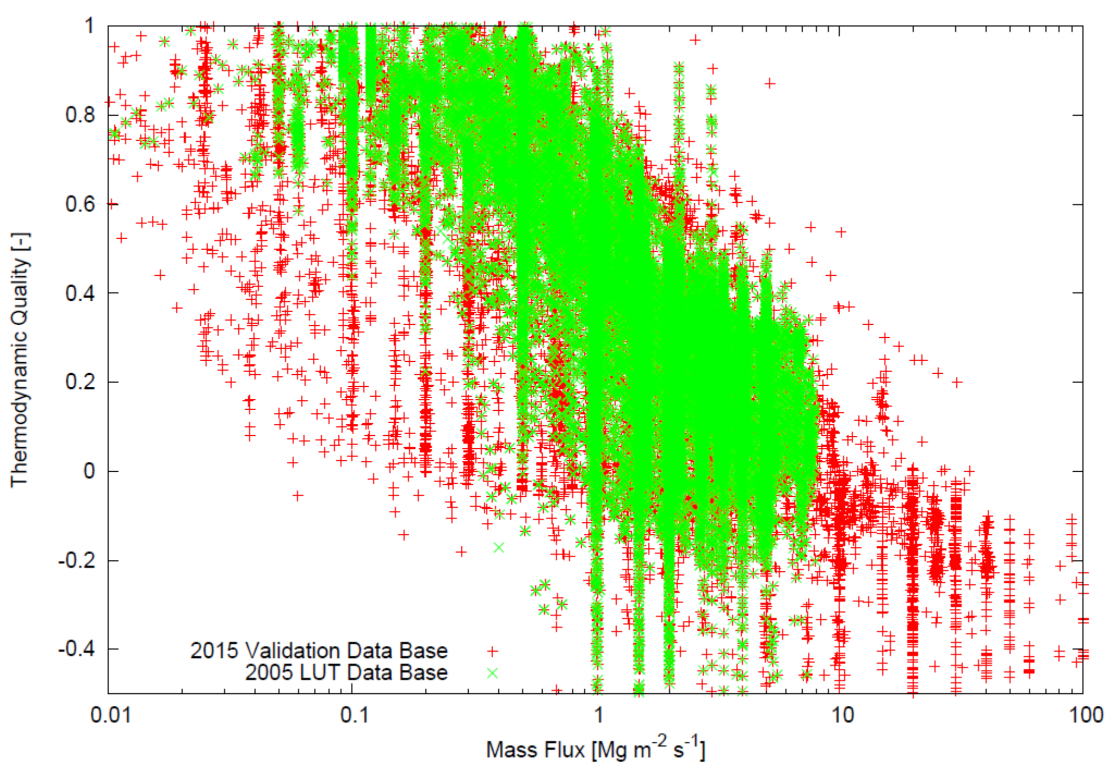

Figure 6-4 CHF Data Coverage on a Quality Versus Mass Flux Map

6.2 Reliability of the Critical Heat Flux Lookup Table Entries

Appendix III shows the complete CHF LUT. In the condensed CHF LUT (as reported in Groeneveld et al. (2007)), four levels of shading were applied to highlight regions of uncertainty. The uncolored entries represent areas that were derived directly from the experimental data and, hence, have the least uncertainty. The light gray regions represent calculated values based on selected prediction methods that provide reasonable predictions under neighboring conditions where experimental data are available. The uncertainty in this region depends on the level of extrapolation from data-based regions. The uncertainty is expected to be small at conditions slightly beyond the range of data, but it becomes larger as the extrapolation is further beyond this range. The medium gray regions represent conditions for which CHF values were often impossible to obtain, including (1) conditions for which critical flow may exist, (2) coolant enthalpies, where the bulk of the liquid starts to become solid ($T_{bulk} < 0.01$ degree C), and (3) G = 0, where the concept of flow quality becomes imaginary. Those regions are included only to improve interpolation accuracy of other regions. Extrapolation into the medium gray region should be avoided. Finally, the dark gray entries represent the LQR, where rapid changes in CHF versus quality curve can be observed. Note that the LQR does not occur at all pressures and mass fluxes. The shading coding can be extrapolated to the complete CHF LUT in Appendix III for conditions where no shading was shown (e.g., P = 4, 8, 9, and 11 MPa).

6.3 Additional Data Sets Not Used To Derive the 2006 Critical Heat Flux Lookup Table

Besides the above data sets, the literature includes a number of additional CHF data sets for upward water flow in vertical tubes. The current CHF database does not yet include these data sets. These data sets need to be transcribed from the reports and compiled into a database. Section II-3 of Appendix II includes references to these additional data sets.

6.4 Application to Geometries Other Than Upflow in 8-Millimeter Tubes

The LUT was based solely on CHF data obtained in directly heated tubes within the diameter range of 3 to 25 mm. The CHF values measured in tubes having diameters other than 8 mm (CHF_D) were normalized to an equivalent CHF value in an 8-mm tube (CHF_8) using the relationship $CHF_8 = CHF_D \left(\frac{D}{8}\right)^n$. In the derivation of the LUT, various values of the exponent n were used; the optimum value was found to be close to n = 0.5, and this value was used for the derivation of the 2006 CHF LUT.

When applying the LUT to subcooled conditions, Tanase et al. (2009) found a slight improvement in prediction accuracy when they used a value of n = 0.33. Mishima et al. (1985, 1987) noted that, for flooding-type CHF (low-flow and low-pressure conditions), the CHF increases with an increase in diameter; therefore, they recommended a negative exponent, n = -0.2 to -0.3, for those specific conditions.

Various investigators have applied the CHF LUT to bundle geometries. When applying the LUT in a subchannel code, the common practice has been to correct the CHF LUT by using the equivalent diameter in the above equation. This practice ignores the possible effect of having a convex surface instead of a concave surface. Doerffer et al. (1994, 1997) compared the CHF in internally heated and bilateral heated annuli and concluded that the CHF on the inner rod in annuli (after correcting for the equivalent diameter effect) is lower than it is in tubes, especially

at higher qualities, whereas the reduction in CHF is least or nonexistent at subcooled conditions. They proposed correction factors that depend on geometry and flow conditions.

Rod-spacing devices, such as grids or endplates and spacers in Canadian deuterium uranium (CANDU) reactors, are known to enhance CHF. The spacer effect decays exponentially downstream from the rod-spacing device according to $CHF = CHF_0 \left(1 + a\, e^{-b\frac{L}{D}}\right)$, where CHF_0 is the undisturbed CHF, L/D is the nondimensional distance from an upstream spacing device, and the constant *a* depends on the flow blockage of the spacing device (Groeneveld et al., 1999, 2001). Groeneveld et al. (1996, 1999) made some interim recommendations based on data from CANDU-type bundles, but their application to mixing vane grids is questionable. In general, the CHF enhancement aspects for the various mixing vane designs is proprietary information that fuel vendors generally do not release. Groeneveld et al. (1999) have also recommended various bundle-CHF correction factors that can be used in conjunction with the CHF LUT to predict the CHF in new bundle geometries for which CHF data are not yet available.

7 CONCLUSIONS AND FINAL REMARKS

- Because of the proliferation in CHF correlations (greater than 500) and CHF models (greater than 50) and because of the limited range of applicability of the models and correlations, an urgent need for a more generalized CHF prediction technique is obvious. The CHF LUT was developed in response to this need.
- The CHF LUT is basically a normalized databank. Compared to other available prediction methods, the LUT approach has the following advantages: (1) it has greater accuracy, (2) it has a wider range of application, (3) it can predict the correct asymptotic trend(s), (4) it requires less computing time, and (5) it can be easily updated if additional data become available.
- Despite the large database (over 40,000 data points), noticeable gaps still exist in the database at flow conditions for which CHF data are not available. The primary conditions under which data are scarce or missing are (1) high flows and high qualities, (2) low flows and low qualities, and (3) pressure ranges of 0.2 to 0.5 MPa.
- The uncertainty in the regions where data are scarce or nonexistent depends on the level of extrapolation from data-based regions. The uncertainty is expected to be small at conditions slightly beyond the range of data, but it becomes larger as the extrapolation is further beyond this range.
- Since the derivation of the 2006 CHF LUT, additional data sets have become available. Sections II-2 and II-3 of Appendix II provide references to the additional data sets. These additional data sets can be used to update the CHF LUT or to independently validate the CHF LUT.
- The CHF LUT was derived based on data from 62 data sets obtained during the past 65 years. Some data lack sufficient information to assess the uncertainty of the data. The ideal (but expensive) approach for removing the uncertainty in the database is to perform an extensive CHF experimentation by a reputable thermal-hydraulic laboratory covering all attainable[2] conditions of the CHF LUT.

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[2] Some conditions correspond to critical flow; estimated CHF values were included in the LUT only to facilitate extrapolation from adjacent CHF conditions.

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APPENDIX A

SUMMARY DESCRIPTIONS OF CRITICAL HEAT FLUX EXPERIMENTAL DATA USED TO DERIVE THE 2006 CRITICAL HEAT FLUX LOOKUP TABLE

Alekseev et al. (1964)

The original reference is in Russian and did not contain the numerical data, but the data plots were of good enough quality for extraction using graphical digitization techniques. However, the data used for the lookup table (LUT) derivation were taken from Kirillov's database (1,064 data points were labeled as "Alekseev 1964"), which was in digital form and was transferred to the University of Ottawa (UofO) in 1991. Kirillov presumably obtained the Alekseev et al. data directly from Alekseev. The table below lists the ranges of conditions of the data set.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
1,064	10.00 10.01	1.000 4.966	9,800 19,610	216 7,566	-0.866 0.944	57 1,398	134 4,949	139.77 357.93

REFERENCE:

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Alessandrini et al. (1963)

Alessandrini et al. (1963) obtained data for upward flow of steam-water mixtures in vertical tubes. The data set contained 753 data points of which 161 were used to derive the 2006 LUT. The two test sections (G1 and G2) were made from seamless American Iron and Steel Institute (AISI) Type 321 (G1) or 304 (G2) stainless steel tubing. The heated length varied from 0.796–2.456 meters with a uniform heat flux distribution. The inlet quality varied from 0.208 to 0.677. The following effects were also investigated:

- the effect of the heated length (L) or of the length-to-diameter (L/D) ratio on the CHF
- the influence of a mixer at the inlet of the test section and a steam separator at the outlet of the test section on the critical heat flux (CHF)
- the effect of an intermediate nonheated section between two heated sections

The table below lists the ranges of conditions that the CHF test covered.

Tube Diameter	Tube Length	Heated Length	Pressure	Mass Flux	Local Quality	Heat Flux	Inlet Temperature
mm	m	m	kPa	kg m^{-2} s^{-1}	-	kW m^{-2}	°C
15.2 (G2) 24.9 (G1)	2.917 (G1) 2.916 (G2)	0.796 2.456	4,874 5,099	1,080 3,990	-0.05 0.74	214 3,662	186 266

REFERENCE:

Alessandrini, A., G. Peterlongo, and R. Ravetta (1963), "Large Scale Experiments on Heat Transfer and Hydrodynamics with Steam-Water Mixtures: Critical Heat Flux and Pressure Drop Measurements in Round Vertical Tubes at the Pressure of 51 kg/cm^2 abs.," CISE-R-86, Centro Informazioni Studi Esperienze (CISE), Milan, Italy.

Babarin et al. (1969)

The Babarin et al. (1969) CHF data set for upward flow in a smooth tube contained 163 data points. The test section was a vertical, uniformly heated stainless steel tube with a 12-millimeter (mm) inner diameter (ID) and a heated length varying from 0.96 to 1.8 m. The quality was calculated from a heat balance. Because the CHF equals zero at the maximum critical quality of 1.0 and this data set has 49 CHF data points with quality greater than 1, the accuracy of the complete data set is in question. The table below lists the ranges of conditions covered by the CHF test.

Tube Diameter	Tube Length	Pressure	Mass Flux	Heat Flux	Thermodynamic Quality	Inlet Temperature
mm	m	kPa	kg m^{-2} s^{-1}	kW m^{-2}	-	°C
12	0.96 1.8	290 304	50 500	190 2,300	0.4665 1.0903	15 124

REFERENCE:

Babarin, V.P., R.I. Sevast'yanov, and I.T. Alad'yev (1969), "A Special Hydrodynamic Effect on the Boiling Crisis in Tubes," Heat Transfer—Soviet Research 1(4):34–41, July 1969.

Babcock and Hood (1962)

The Babcock and Hood 1962 data are virtually the same as the Hood (1962) data although Hood (1962) has approximately 50 percent more data, which is not surprising because the source is also the same. The slight differences (within a few percentage points) are probably the result of the different unit conversions and properties used. The table below lists the test conditions.

Number of data points	Tube Diameter	Heating Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
39	8.00 22.5	0.61	413 6,890	2,946 11,452	-0.187 -0.05	202 639	4,876 10,546	19 177

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Babcock, D.F., and R.R. Hood (1962), "Heavy Water Moderated Power Reactors," DP-725, E.I. Dupont de Nemours and Company, Wilmington, DE.

Baek (2001)

An electronic copy of this data set was obtained in private communication with the author, W.-P. Baek, from the Korean Advanced Institute of Science and Technology (KAIST). This data set is sometimes referred to as "Baik (2001)." Details of the experiment are not known except that the CHF corresponds to a sharp wall temperature rise of about 100 degrees Kelvin above the saturation temperature. This data set contains 63 data points of which 34 were used for the LUT derivation. The table below lists the ranges of flow parameters.

Tube Diameter	Heated Length	L_h/D ratio	Pressure	Mass Flux	Heat Flux	Critical Quality	Inlet Temperature
mm	m	-	kPa	kg m^{-2} s^{-1}	kW m^{-2}	-	°C
6.0 10.0	0.180 0.480	30.0 80.0	101.0 3,618.0	299.0 2,032.0	1,222.0 7,412.8	-0.109 0.099	5.9 40.2

REFERENCE:

Baek, W.-P. (2001), KAIST, Korea. Data obtained through private communication with D.C. Groeneveld.

Bailey (1977)

The vertical test section was made from a 15-mm-ID (18-mm outside diameter) Inconel tube and had a uniformly heated length of 5.4 meters. The test section was instrumented with 58 thermocouples attached to the tube in diametrically opposed pairs, generally every 76 mm. The experiments were performed by measuring the CHF occurrence at the outlet and by subsequently increasing the power such that the CHF spread upstream and post-CHF temperatures could be measured. The report contains tables of CHF data. The table below lists ranges of flow parameters.

Tube Diameter	Pressure	Mass Flux	Heat Flux	Thermodynamic Quality	Surface Temperature
mm	kPa	kg m^{-2} s^{-1}	kW m^{-2}	-	°C
15	1,370 6,990	49 668	84 799	0.78 1.21	200 697

The post-CHF temperatures can be extracted from Figures 8–17 (Bailey, 1977) in which the wall temperature is plotted as a function of thermodynamic quality.

REFERENCE:

Bailey, N.A. (1977), "Dryout and Post Dryout Heat Transfer at Low Flow in a Single Tube Test Section," AEEW-R 1068, United Kingdom Atomic Energy Authority, Harwell, United Kingdom (United Kingdom).

Bailey and Lee (1969)

This CHF data set contains 158 data points. The test section consisted of a vertical tube through which the water flowed upwards. The tube was made from commercial stainless steel-grade AISI 316. Inlet and outlet bulk temperatures were measured with chromel-alumel thermocouples. For greater accuracy, Chromel/Constantan thermocouples were used for the wall temperature measurement. The table below lists the ranges of flow parameters.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
158	9.30	3.05	6,895 18,340	958 4,242	0.069 0.727	54 604	344 2,221	199 347

REFERENCE:

Bailey, N.A., and D.H. Lee (1969), "An Experimental and Analytical Study of Boiling Water at 2,000 to 2,600 psi. Part I: Dryout and Post-Dryout Heat Transfer," AEEW-R 659, United Kingdom Atomic Energy Authority, Harwell, United Kingdom.

Becker et al. (1963)

This experiment obtained 809 burnout measurements covering the conditions listed in the table below.

Tube Diameter	Heated Length	Pressure	Mass Flux	Steam Quality	Heat Flux	Inlet Subcooling
mm	mm	kg cm^{-2}	kg m^{-2} s^{-1}	-	W cm^{-2}	°C
10.04 (except for L_h = 600 mm where the ID = 9.9 mm)	600 2,500	5.3 37.3	100 1,890	0.20 0.95	50 515	56 212

In the graphically presented results, the burnout steam quality (X) was plotted against the pressure with the surface heat flux as parameter. This report did not tabulate any data. After cross-checking the data, it was found that Table 1.2 in AE-177 (Becker et al., 1965) also contains the data (i.e., Report AE-177 contains a compilation of all Swedish tube CHF data up to 1965).

The test section was made of stainless steel tube and was 2,800 mm long with a 10.04-mm ID. During the first test series, the copper power clamps were placed in such a way that the heated length was 2,500 mm. Afterwards, the lower power clamp was moved upwards in steps of 250 mm so that heated lengths of 2,250, 2,000, 1,750, 1,500, 1,250, and 1,000 mm were obtained. In addition, the report includes runs performed with a test section having a 9.96-mm ID and 600-mm heated length.

To protect the test section, a burnout detector was used to switch off the power supply when excessive temperatures occurred in the last 100-mm length of the test section. The excessive temperature often occurred suddenly, indicating that burnout conditions had been reached. Burnout always occurred just below the upper power clamp.

REFERENCES:

Becker, K.M., P. Persson, L. Nilsson, and O. Eriksson (1963), "Measurements of Burnout Conditions for Flow of Boiling Water in Vertical Round Ducts," AE-114 (Part 2), Aktiebolaget Atomenergi, Stockholm, Sweden.

Becker, K.M., O. Hernborg, M. Bode, and O. Eriksson (1965), "Burnout Data for Flow of Boiling Water in Vertical Round Ducts, Annuli and Rod Clusters," AE-177, Aktiebolaget Atomenergi, Stockholm, Sweden.

Becker (1965)

AE-177 (Becker et al., 1965) and AE-178 (Becker, 1965) basically compile all Swedish CHF data up to 1965.

Table I of AE-177 contains the tables of the burnout data obtained in Sweden by Becker for flow in vertical channels at the Heat Engineering Laboratory of AB Atomenergi in Stockholm, Sweden. The data are a compilation of Swedish CHF data obtained in tubes, annuli, and three- and seven-rod clusters.

Table I in AE-177 contains 3,473 round tube data points, including the tube CHF data of Becker et al. (1963), as follows:

- Table I.1 in AE-177 contains 571 data points that are also found in CD Spreadsheet "CHF Data for 2006 LUT.xls" (#901–1459).

- Table I.2 in AE-177 contains about 1,787 data points. The first 162 data points are also found in CD Spreadsheet "CHF Data for 2006 LUT.xls" (#1490–1649). Runs 163–971 are the same data from AE-114 (Becker et al., 1963) and are found in CD Spreadsheet "CHF Data for 2006 LUT.xls" #1650-2458. For run numbers greater than 971, the data are again found in CD Spreadsheet "CHF Data for 2006 LUT.xls", while some of the runs are duplicated in Table 1.2 in AE-178.

- The 273 CHF data points in Table 1.3 in AE-177 are also found in CD Spreadsheet “CHF Data for 2006 LUT.xls” while some of the data are duplicated in Table 1.3 in AE-178. All data in CD Spreadsheet “CHF Data for 2006 LUT.xls” were used to derive the 2006 CHF LUT.

- Table I.4 in AE-177 contains 811 CHF data points that also appear in Table 1.4 in AE-178, but Table 1.4 in AE-177 contains an additional 32 data points obtained in a 20.02-mm tube. The first 665 runs are also in the CD Spreadsheet “CHF Data for 2006 LUT.xls” (#5005–5664).

The tables in AE-178 include the following:

- Table I in AE-178 comprises Table 1.2 (P = 2.7–31), Table 1.3 (P = 41), and Table 1.4 (P > 41 kilograms per square meter (kg/m2)). Table I.2 contains about 460 Swedish CHF data points, Table I.3 contains about 28 data points, and Table I.4 contains about 770 CHF data points (in total, about 1,258 data points). In Table 1.4 of AE-178, runs 1–665 were the same as CD Spreadsheet “CHF Data for 2006 LUT.xls” runs (#5005–5664). However, runs 666–861 of Table I.4 obtained in 19.93- and 24.95-mm tubes could not be located in the CD Spreadsheet “CHF Data for 2006 LUT.xls” database because the tube diameter greater than 16 mm was possibly outside the range of interest of the CHF LUT.

- Table II in AE-178 contains about 400 tube CHF data points labeled as “Columbia University Ref. 7,” which refers to the following report:

  – Babcock, D.F. (coordinator), “Heavy Water Moderated Power Reactors,” Progress Reports May–June 1963 and January–February 1964, Atomic Energy Commission Research and Development Reports DP-855 and DP-895, Savannah River Laboratory, Aiken, South Carolina.

- These data were obtained in tubes with IDs ranging from 6.22 to 37.47 mm and pressures ranging from 52.7 to 105.7 kilograms per square centimeter (kg/cm^2). These data apparently were not used for the 2006 CHF LUT derivation.

- Table III of AE-178 contains 626 CHF tube measurements labeled as “Winfrith Data Ref. 13,” which refers to the following reference:

  – Lee, D.H., and J.D. Obertelli (1963), “An Experimental Investigation of Forced Convection Boiling in High Pressure Water,” AEEW-R 213, United Kingdom Atomic Energy Authority, Harwell, United Kingdom.

- The Table III data were obtained in tubes with IDs ranging from 5.59 to 11.46 mm and pressures ranging from 40 to 135 kg/cm^2. The original Lee and Obertelli reference is contained in the supplementary CHF database in Section 6.3 , but these data were not used for the 2006 CHF LUT derivation.

The table below lists test conditions taken from AE-178. The 811 CHF measurements were obtained in a tube with an ID of 9.98 mm. Reference is also made to the earlier 488 measurements by Becker in tubes at pressures of 2.7, 10, 20, and 30 kg/cm^2, which appear in Table 1.2 in AE-178.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux
number	mm	m	kPa	kg m^{-2} s^{-1}	-	K	kW m^{-2}
811	9.98	1–3.5	4,100–10,100	222–3,477	0.01–0.98	56–240	510–4,340
?	3.93–24.97	1–2.5	3,100–7,100	220–5,450	0–0.96	53–230	1,000–5,700

The processed data appear to be confusing. Runs 1–843 of the processed data correspond to the data of Table I.4 in both AE-177 and AE-178. However, the authors have been unable to find the source of the data for runs 1001–1500. These data appear in the CD Spreadsheet "CHF Data for 2006 LUT.xls" file (#5666–6049).

REFERENCES:

Becker, K.M. (1965), "An Analytical and Experimental Study of Burnout Conditions in Vertical Round Ducts," AE-178, Aktiebolaget Atomenergi, Stockholm, Sweden.

Becker, K.M., O. Hernborg, M. Bode, and O. Eriksson (1965), "Burnout Data for Flow of Boiling Water in Vertical Round Ducts, Annuli and Rod Clusters," AE-177, Aktiebolaget Atomenergi, Stockholm, Sweden.

Becker (1970)

The purpose of this experiment was to investigate the CHF at conditions not covered by Becker's previous experiments (i.e., in tubes with an ID of 2.40, 3.00, and 36.05 mm at pressures of 30, 50, and 70 bar). The small diameter tubes had a heated length of 500 mm, and the heated length of the large diameter tube was 1,880 mm. Because of limitations on the available power supply, only low-flow (95–428 kilograms per square meter per second (kg m^{-2} s^{-1}) CHF measurements were possible for the large diameter tube. The mass flux range for the small diameter tube was 290 to 2,725 kg m^{-2} s^{-1}. The report tabulated the CHF measurements. Of the 113 CHF measurements obtained in the 2.4- and 3.0-mm tubes, 69 were included in the CD Spreadsheet "CHF Data for 2006 LUT.xls" data file (#13142–13211) and were used in the 2006 LUT derivation. The 47 CHF measurements obtained for the tube with an ID of 36.03 mm were not used in the derivation of the 2006 LUT because the diameter was too large.

Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
2.40 36.05	0.500 1.880	3,050 7,100	93.3 2,725	0.207 0.903	371 1,065	1,026 5,130	51.75 113.22

REFERENCE:

Becker, K.M. (1970), "Burnout Measurements in Vertical Round Tubes, Effect of Diameter," TPM-RL-1260, Aktiebolaget Atomenergi, Teknisk PM, Stockholm, Sweden, December 1970, 16 pages.

Becker et al. (1971)

This report contains a large amount of data (1,650 data points) obtained in 10-mm-ID tubes with a heated length of 1, 2, 3, and 4.966 meters (Becker et al., 1971). This database contains 90 CHF data points obtained in a 10-mm-ID tube having a 2-meter heated length with pressures of 3-, 5-, 7-, and 9 megapascals (MPa). These data points, also reported by Nilsson (1970), were used as part of the European CHF reproducibility exercise (CISE, 1970). The database used to derive the LUT (see CD Spreadsheet "CHF Data for 2006 LUT.xls") contains 1,435 data points (Data #13240–14674 from Becker et al. (1971)) obtained in about 10-mm-ID tubes.

Tube Diameter	Heating Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
10.00 10.01	1.000 4.966	3,000 20,000	156 8,111	-0.866 1.061	26 1,414	135 5,476	124.75 358.65

REFERENCES:

Becker, K.M., G. Strand, D. Djursing, O. Eklind, K. Lindberg, and C. Österdahl (1971), "Round Tube Burnout Data for Flow of Boiling Water at Pressures Between 30 and 200 bar," KTH-NEL-14, Royal Institute of Technology, Stockholm, Sweden.

Nilsson, L. (1970), "Repeatability Tests of Critical Heat Flux Data for 1970 Meeting of the European Two-Phase Flow Group, Comparison of Results by Becker's Burnout Correlation," AE-TPM-RL-1229, Aktiebolaget Atomenergi, Stockholm, Sweden, June 1970, 24 pages.

CISE (1970), "Exercise on Reproducibility of Critical Heat Flux Data, Presentation of Experimental Results," CISE Meeting of the European Two-Phase Flow Group, Segrate, Milan, Italy, June 8–11, 1970.

Bennett et al. (1965)

Bennet et al. (1965) performed the CHF experiments in the United Kingdom Atomic Energy Authority's Harwell high-pressure loop using stainless steel tubular test sections. Most tests were performed inside 0.497-inch tubes, but tests using a limited test matrix were also performed in tubes with a nominal 3/8-inch bore. The latter tests investigated the effect of wall thickness by varying the thickness from 0.036 inch to 0.082 inch. The effect was negligible.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
201	9.22 12.62	1.524 5.563	6,612 7,481	623.8 5,844.4	0.026 0.948	21 691	589.6 3,299.7	157.67 279.45

REFERENCE:

Bennett, A.W., G.F. Hewitt, H.A. Kearsey, and R.K.F. Keeys (1965), "Measurements of Burnout Heat Flux in Uniformly Heated Round Tubes at 1,000 psia," AERE-R 5055, United Kingdom Atomic Energy Authority, Harwell, UK.

Bergelson (1980)

The data set labeled as "Bergelson" was used for the 2006 LUT derivation and was part of the data compilation transferred to UofO by Kirillov. The paper labeled as "Bergelson (1980)" does not contain these data; instead, it contains only subcooled CHF data obtained under forced convective conditions in several fluids, including a few water data, in graphical form. The table below lists the ranges of CHF test conditions.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg-1	kW m^{-2}	°C
328	8.00	0.241 0.400	170 3,080	1,927 7,078	-0.295 0.090	96 853	3,511 14,571	28.94 169.20

REFERENCE:

No reference.

Bergles (1963)

Bergles performed subcooled CHF tests at the Massachusetts Institute of Technology test facility using small-diameter tubing (stainless steel) at low pressure with variable wall thickness (0.006 to 0.036 inch) and short heated lengths. The effect of wall thickness was found to be insignificant. The CHF decreased with increasing diameter. The table below lists the ranges of flow conditions.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
117	0.62 6.21	0.011 0.155	140 586	1,518.7 24,272.4	-0.137 0.111	25 534	4,957.1 44,713	3.10 116.55

The data were extracted from Figures 3–8 (Bergles, 1963) using graphical digitization techniques. This introduces additional errors. Only seven data points were used for the 2006 LUT derivation.

REFERENCE:

Bergles, A.E. (1963), "Subcooled Burnout in Tubes of Small Diameter," 63-WA-182, American Society of Mechanical Engineers Winter Annual Meeting, Philadelphia, PA, November 17–22, 1963.

Borodin and Macdonald (1983) and Leung (1982)

These two references refer to the same data set, which was measured by Borodin and MacDonald (1983) at Atomic Energy of Canada Limited (AECL) in Chalk River, Ontario, Canada, but analyzed by Leung (1982). Because of the restricted distribution of this data, the test parameters and CHF data are not included here.

REFERENCES:

Borodin, A. (1983), AECL Internal Report CRNL-2538. Restricted Distribution.

Leung, A. (1982), "A study of the CHF Performance of Light and Heavy Water in Long Vertical Tubes," AECL Power Projects Report AI-1024, Sheridan Park, Canada. Restricted Distribution.

Burck and Hufschmidt (1965)

CHF measurements were obtained for subcooled water in directly heated 10-mm-ID tubes. The tube material was not specified (likely stainless steel). The authors refer to a special burnout detector, which was described elsewhere (i.e., the reference is not available). The table below lists the ranges of flow conditions.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
143	10.0	0.35	1,100 3,090	917 3,756	-0.246 0.087	532 939	4,500 12,200	16.7 60.8

REFERENCE:

Burck, E., and W. Hufschmidt (1965), "Measurement of the Critical Heat-Flux-Density of Subcooled Water in Tubes at Forced Flow," EUR 2432.d, Australian Atomic Energy Commission, Research Establishment, Sydney, Australia, Translated by J.B. Hopkinson, July 1969, LIB/TRANS 210, 40 pages.

Celata et al. (1992a)

This data set is referred to as "Celata et al. (1992a)" in Table 4-2 of this report. Tests were performed in 6- and 8-mm-ID tubes having a wall thickness of 0.25 mm and very short heated

lengths (10 to 15 centimeters (cm)). Because of the high subcooling, the CHF was very high, which physically damaged the test section when CHF conditions were reached. The table below lists the ranges of flow conditions.

No. of Data Points	Tube Diameter	Heating Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
60	6.00 8.00	0.10 0.15	398 5,120	2,019 10,046	-0.517 -0.106	350 1,018	7,428 29,514	29 81

REFERENCE:

Celata, G.P., M. Cumo, and A. Mariani (1992a), "CHF in Highly Subcooled Flow Boiling with and without Turbulence Promoters," Meeting of the European Two-Phase Flow Group, Paper C1, Stockholm, Sweden, June 1–3, 1992, 14 pages.

Celata et al. (1992b)

This data set is referred to as "Celata et al. (1992b)" in Table 4-2 of this report. Tests were performed in 2.5- and 5-mm-ID tubes made of Type 304 stainless steel and short (20- to 40-cm) heated lengths. Because of the high subcooling, the CHF was very high, which physically damaged the test section when CHF conditions were reached. The table below lists the range of flow conditions.

No. of Data Points	Tube Diameter	Heating Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
78	2.50 5.00	0.20 0.40	107 2,181	2,166 32,637	-0.091 0.287	345 790	5,347 42,777	19 55

REFERENCE:

Celata, G.P., M. Cumo, and A. Mariani (1992b), "Subcooled Water Flow Boiling CHF with Very High Heat Fluxes," Revue Générale de Thermique 31(362):106–114.

Celata and Mariani (1993)

The Celata and Mariani (1993) database contains 1,887 CHF data points from 23 references that had been scanned and digitized in the 1990s; 1,357 of these data points were obtained in round tubes and were tabulated separately. This database was transferred to UofO by G.P. Celata (see Celata (1993) below).

The data are from (1) Reference 2 of Celata and Mariani (1993), which is also referred to as "Celata et al. (1993)" (see the *International Journal of Heat and Mass Transfer* article referenced below) and (2) Reference 4 of Celata and Mariani (1993), which is an unpublished report from the Italian National Agency for New Technologies and Sustainable Economic Development (ENEA) and therefore not available.

REFERENCES:

Celata, G.P., and A. Mariani (1992), "A Data Set of Critical Heat Flux in Water Subcooled Flow Boiling," Addendum to the Specialists' Workshop on the Thermal Hydraulics of High Heat Flux Components in Fusion Reactors, ENEA, Casaccia, Rome, Italy, September 9–12, 1992.

Celata, G.P., M. Cumo, and A. Mariani (1993), "Burnout in Highly Subcooled Flow Boiling in Small Diameter Tubes," International Journal of Heat and Mass Transfer 36:1269–1285.

Celata, G.P. (1993), Personal communication letter between G.P. Celata and Professor S.C. Cheng, University of Ottawa, Ottawa, Ontario, Canada, April 22, 1993.

Celata et al. (1993)

These CHF experiments were designed in support of fusion reactors that require very high heat flux removal rates (up to 60 megawatts per square meter) from the diverters. The experiments were performed in small diameter stainless steel (2.5-mm-ID) tubes with a wall thickness of 0.25 mm and a heated length of 100 mm. It is unclear whether Celata et al. (1993) used these data for the LUT derivation. The table below lists the ranges of test conditions.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
78	2.50	0.10	578 2,714	11,240 40,000	-0.357 -0.104	387 844	12,113 60,579	30 70.5

REFERENCE:

Celata, G.P., M. Cumo, and A. Mariani (1993), "Burnout in Highly Subcooled Water Flow Boiling in Small Diameter Tubes," International Journal of Heat and Mass Transfer 36(5):1269–1285.

Cheng et al. (1983a, 1983b)

The original references for these two data sets are no longer available. Cheng and his students performed CHF tests on the low-pressure UofO test facility. The table below lists the ranges of test conditions.

No. of Data Points	Tube Diameter	Heating Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}
150	12.60	0.370 0.740	101 687	50 400	0.187 1.227	42 210	331.2 2,115
132	4.80	0.19 0.38	100 700	300 750	0.082 0.765	42 214	889 2,131

REFERENCES:

Cheng, S.C., K.T. Poon, P. Lau, K.T. Heng, T. Doan, and C.Y. Chan (1983a), "CHF Experiments and Construction of CHF Table," University of Ottawa, Ottawa, Ontario, Canada, AECL Contract, 1st Progress Report, July 1982–March 1983.

Cheng, S.C., K.T. Poon, T. Doan, S.K. Chin, and Y.M. Koo (1983b), "CHF Experiments and Construction of CHF Table," University of Ottawa, Ottawa, Ontario, Canada, AECL Contract, Contract Report No. 2, December 1983.

CISE (1970)/Nilsson (1970) European CHF Reproducibility Exercise

Because of concerns that CHF measurements could vary significantly between different laboratories even though the test equipment and the test conditions were nominally identical, the European Two-Phase Group decided to perform a so-called "CHF reproducibility" exercise. The objective of this reproducibility exercise was to determine the variation in CHF measurements between various laboratories. CISE (1970) and Nilsson (1970) reported the results of this exercise. The very large CISE report contains individual chapters written by each of the participating laboratories. Nilsson's report (1970) also contains all individual data sets (i.e., a total of 594 CHF measurements were taken by the participating laboratories) and describes the analysis of the data.

The following organizations/laboratories participated in the exercise:

- AB Atomenergi (AE), Nyköping, Sweden
- Allgemeine Elektricitäts-Gesellschaft AG, Telefunken, Frankfurt am Main, Germany
- Commissariat à l'Energie Atomique, Paris, France
- CISE, Milan, Italy
- EUR, Ispra, Italy
- Maschinenfabrik Augsburg-Nurnberg AG, Munich, Germany
- Società Ricerche Impianti Nucleari (Sorin), Italy
- United Kingdom Atomic Energy Authority, Harwell, United Kingdom

The table below lists the nominal test conditions.

Tube Diameter	Heating Length	Pressure	Mass Flux	Inlet Subcooling
mm	m	MPa	kg m^{-2} s^{-1}	kJ kg^{-1}
10	2	3, 5, 7, and 9	260 6,000	15 3,235

The above ranges of conditions were the maximum ranges; the ranges of conditions were different for the various laboratories.

The discrepancy in CHF values was expected to be within 10 percent; however, the discrepancy initially exceeded 30 percent. After careful examination of the two outliers (the other laboratories were within 10 percent), two laboratories found inconsistencies in their measurement approach and hardware (which may have given rise to flow instabilities), and one laboratory withdrew its results.

REFERENCES:

CISE (1970), "Exercise on Reproducibility of Critical Heat Flux Date—Presentation of Experimental Results," Meeting of the European Two-Phase Group, June 9–11, 1970, Milan, Italy.

Nilsson, L. (1970), "Repeatability Tests of Critical Heat Flux Data for [the] 1970 Meeting of the European Two-phase Flow Group, Comparison of Results by Becker's Burnout Correlation," AE-TPM-RL-1229, Aktiebolaget Atomenergi, Stockholm, Sweden, 23 pages.

Dell et al. (1969)

Burnout heat flux measurements were reported for water flowing upward in a 0.243-inch ID stainless steel tube. Tube lengths of up to 217 inches were used, which gave an L/D ratio higher than that used in previous experiments. CHF occurrence was detected by a Wheatstone bridge at the end of the heated length where CHF occurred first (i.e., because stainless steel has a fairly high temperature coefficient of resistivity, it is suitable for use as a part of the Wheatstone circuit). CHF values were obtained for mass velocities of $1x10^6$, $2x10^6$, and $3x10^6$ pounds per hour per square foot with an outlet pressure of 1,000 pounds per square inch, absolute (psia).

No. of Data Points	Tube Diameter	Heating Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}
82	6.17	0.914 5.512	6,895	14,328.9 4,135.8	0.144 0.779	79 365	492.7 3,340.4

REFERENCE:

Dell, F.R., G.F. Hewitt, R.K.F. Keeys, and R.A. Stinchcombe (1969), "Burnout Heat Flux Measurements in a Long Tube," AERE-M 2216, Atomic Energy Research Establishment, Harwell, United Kingdom, June 1969, 16 pages.

Doerffer (1999)

This proprietary data set belongs to AECL. The electronic copy of this data set was obtained through private communication with the author. An AECL unpublished report contains details of the experiment. Because the data set is proprietary, the test parameters and CHF data are not included here.

REFERENCE:

Personal communication with D.C. Groeneveld (original reference: Doerffer, S. (1999), "Effect of Flow Orientation on CHF in Smooth Tubes," AECL unpublished report).

Doerffer et al. (1997)

This proprietary data set belongs to AECL. The electronic copy of this data set was obtained through private communication with the author. An AECL unpublished report contains details of the experiment. However, a recent paper by Doerffer and Groeneveld (1999) describes the same data set. Because the data set is proprietary, the test parameters and CHF data are not included here.

REFERENCES:

Doerffer, S., K.F. Rudzinski, and D.C. Groeneveld (1997), "Fluid-to-Fluid Modelling of CHF Enhancement in a Tube," AECL unpublished report RC-1922, Atomic Energy of Canada Limited, Chalk River, Ontario, Canada.

Doerffer, S., and D.C. Groeneveld (1999), "Fluid-to-Fluid Modelling of CHF Enhancement in a Tube," in the Proceedings of the 9th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-9), San Francisco, CA, October 3–8, 1999.

Era et al. (1966)

CHF data were extracted from this post-dryout experiment. The accuracy of the results depends on the axial spacing of the thermocouples (20 cm in this experiment) and, therefore, is slightly below that of regular CHF tests. The tests were performed using an 8-mm-ID stainless steel tube with a heated length of 4.8 m. The wall thickness was 1.5 mm. The table below lists the test conditions.

No. of Data Points	Tube Diameter	Heating Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux
number	mm	m	kPa	$kg\ m^{-2}\ s^{-1}$	-	$kJ\ kg^{-1}$	$kW\ m^{-2}$
163	5.98	1.602 4.800	6,777 7,049	1,105 3,014.9	0.374 0.952	-1,211 565	109.2 1,960.9

REFERENCE:

Era, A., G.P. Gaspari, A. Hassid, A. Milani, and R. Zavattarelli (1966), "Heat Transfer Data in the Liquid Deficient Region for Steam-Water Mixtures at 70 kg/cm² Flowing in Tubular and Annular Conditions," CISE-R-184, Centro Informazioni Studi Esperienze, Milan, Italy, June 1966, 108 pages.

Griffel (1965)

This thesis contains a large amount of CHF data obtained in different diameter tubes. All tubes were made of Type 304 stainless steel. The flow was vertically upwards. These data were used in the derivation of the CHF LUT. The table below lists the test conditions.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux
number	mm	m	kPa	$kg\ m^{-2}\ s^{-1}$	-	$kJ\ kg^{-1}$	$kW\ m^{-2}$
397	6.22 37.46	0.610 1.972	3,448 10,343	637.3 18,577.2	-0.209 0.592	45 1,209	1,400.6 8,107.3

REFERENCE:

Griffel, J. (1965), "Forced Convection Boiling Burnout for Water in Uniformly Heated Tubular Test Sections," Doctor of Engineering Science Thesis, Columbia University, New York, NY.

Groeneveld (1985)

Groeneveld (1985) contains a proprietary data set.

REFERENCE:

Groeneveld, D.C. (1985), AECL internal unpublished report, Atomic Energy of Canada Limited, Chalk River, Ontario, Canada.

Hewitt et al. (1965)

CHF experiments were performed in directly heated stainless steel tubes with vertical flow upwards. Burnout detector trip wires were attached to the exit end of the test section and were connected to a Wheatstone-type bridge, which detected any difference in electrical resistance (resulting from change in tube temperature) between parts of the test section immediately adjacent to the downstream end and the parts just below that. Any imbalance in the bridge actuated the circuit breaker and cut off the electrical power supply. The table below lists the test conditions.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}
442	9.30	0.229 3.048	101 208	90.9 301	0.160 1.083	-41 383	144 4,013

REFERENCE:

Hewitt, G.F., H.A. Kearsey, P.M.C. Lacey, and D.J. Pulling (1965), "Burnout and Film Flow in the Evaporation of Water in Tubes," AERE-R 4864, Atomic Energy Research Establishment, Harwell, United Kingdom, March 1965, 58 pages.

Hood (1962)

These tests were likely obtained using a similar visual burnout detection as described by Hood and Isakoff (1962) (see the section titled, "Hood and Isakoff (1962)," below). The flow was downwards, which probably would not have affected the results because the flow was quite high. The Babcock and Hood (1962) data are virtually the same as the Hood (1962) data although Hood (1962) has about 50 percent more data. This is not surprising because the source is also the same. The slight differences (within a few percentage points) is probably the result of the different unit conversions and properties used. The table below lists the test conditions.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}
45	8, 12.5, 22.2	0.61	414 8,412	2,156 11,390	-0.25 -0.05	204 1,113	5,741 11,830

REFERENCES:

Hood, J.J. (1962), "Heavy Water Moderated Power Reactors," DP-725, E.I. du Pont de Nemours and Company, Wilmington, DE, April 1962, 53 pages.

Babcock, D.F., and R.R. Hood (1962), "Heavy Water Moderated Power Reactors," DP-725, E.I. Dupont de Nemours and Company, Wilmington, DE.

Hood and Isakoff (1962)

Stainless steel tubing was used in these CHF tests with upward flow. In most cases, the burnout occurred within 1/2 inch (and never more than 7/8 inch) from the downstream end of the heated part of the tube. Burnout was detected primarily by the **melting of the tube wall** or **observation of an incandescent spot** on the outside of the tube wall. In some tests, burnout was detected by the change in electrical resistance of the last inch of the heated length. The change in resistance was observed with a null-balance circuit (Wheatstone bridge), which was calibrated during the tests in which the melting of the tube wall occurred.

Only about 50 percent of the measurements were used for the LUT derivation; it is unclear why all the 22.2-mm data and some of the other diameter data were excluded. The table below lists the test conditions.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}
24	8.00 22.2	0.60 1.10	6,895	664 2,726	0.001 0.484	66 1,224	3,186 4,637

REFERENCE:

Hood, J.J., and L. Isakoff (1962), "Heavy Water Moderated Power Reactors," DP-755, E.I. du Pont de Nemours and Company, Wilmington, DE, July 1962, 38 pages.

Inasaka and Nariai (1989)

These high-heat flux burnout tests were performed in a 3-mm tube at highly subcooled conditions. The flow was up to 30 megagrams per square meter per second. No CHF detectors were used. The power was increased gradually, and CHF was recorded when the test section melted. The table below lists the test conditions.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}
29	3.00	0.10	290 1,050	4,300 29,900	-0.188 -0.051	266 626	7,300 44,500

REFERENCE:

Inasaka, F., and H. Nariai (1989), "Critical Heat Flux of Subcooled Flow Boiling with Water," in the Proceedings of the 4th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-4), Karlsruhe, Germany, October 10–13, 1989, Volume 1, pp. 115–120.

Jafri (1993)

The data were obtained from Jafri's doctoral thesis (1993). The data set contains 21 data points for upflow and about 30 data points for downflow. All experimental data refer to the vertical orientation using pure water as a test fluid. The material of test section was Inconel 625 with a wall thickness of 1.65 mm. Eight data points have two phases at the test-section inlet, and the same data points have dryout quality greater than 1; they have been rejected. The table below lists the range of parameters for this data set.

Tube Diameter	Heated Length	L/D Ratio	Pressure	Mass Flux	Local Quality	Inlet Temperature	Heat Flux
mm	m	-	kPa	kg m^{-2} s^{-1}	-	°C	kW m^{-2}
15.7	2.440	155.414	362 1,060	1,439 7,830	0.0947 1	74.4 265	1,800 5,620

REFERENCE:

Jafri, T.M. (1993), "Analysis of Critical Heat Flux for Vertical Round Tubes," Ph.D. Thesis, Columbia University, New York, NY, 164 pages.

Jens and Lottes (1951)

Jens and Lottes (1951) reported on some very early CHF experiments that were performed in tubes. Table II-V in the report contains the data obtained either at the University of California, Los Angeles (UCLA) (see references below), or at Purdue University by Weatherhead (1950). The analysis did not use the Weatherhead data. The table below lists the ranges covered by the UCLA experiment.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
48	5.74	0.625	3,448 13,790	1,301.8 10,603.9	-0.464 -0.015	279 1310	2,965.3 11,924.4	70.52 285.05

It is not clear which reference below refers to the UCLA report (Boelter (1949), Gunther (1951), or McAdams et al. (1948)).

REFERENCES:

Jens, W.H., and P.A. Lottes (1951), "Analysis of Heat Transfer Burnout, Pressure Drop and Density Data for High-Pressure Water," ANL-4627, Argonne National Laboratory, Lemont, IL, May 1, 1951, 73 pages.

Boelter, L.M.K., et al. (1949), "Boiling Studies," U.S. Atomic Energy Commission Research Contract No. AT-11-1-Gen-9, Progress Report No. 1, U.S. Atomic Energy Commission, Washington, DC, August 1949.

Gunther, F.C. (1951), "Photographic Study of Surface-Boiling Heat Transfer to Water with Forced Convection," Transactions of the American Society of Mechanical Engineers, Vol. 73, No. 2, pp. 115-123

McAdams, W.H., J.N. Addonas, and W.E. Kennel (1948), "Heat Transfer at High Rates to Water with Surface Boiling," ANL-4268, reproduced by Argonne National Laboratory, Lemont, IL, December 1948.

Weatherhead, R. (1950), Thesis in Mechanical Engineering, Purdue University, West Lafayette, IN.

Judd and Wilson (1966)

These experiments were performed as part of a series of tests to examine the effect of axial flux shape. This section reports the uniform axial flux distribution (AFD) data. Thermocouples were attached every 1 inch along the downstream part of the test section. The material of the test section was not specified. The table below lists the ranges of conditions covered by the experiment.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
49	11.30	1.829	6,861 13,859	673.9 3,428	0.016 0.776	33 730	593.1 2,668.8	207.11 323.84

REFERENCE:

Judd, D.F., and R.H. Wilson (1966), "Burnout for Flow Inside Round Tubes with Nonuniform Heat Fluxes," BAW-3238-9, Babcock & Wilcox Company, Lynchburg, VA, May 1966, 123 pages.

Kim et al. (2000)

This data set contains 512 CHF data points; however, the author mentions 513 data points. The test sections were made of vertical Inconel 625 tubes through which the subcooled water flowed upwards. Three K-type thermocouples were brazed to the outer surface of the test section to detect CHF. The table below lists the ranges of flow parameters.

Tube Diameter	Heated Length	L_h/D ratio	Pressure	Mass Flux	Critical Quality	Heat Flux	Inlet Temperature
mm	m	-	kPa	kg m^{-2} s^{-1}	-	kW m^{-2}	°C
6.0 12.0	0.300 1.770	41.7 295.0	104.0 951.0	20.0 277.0	0.323 1.251	120.0 1,598.0	20.5 156.3

REFERENCE:

Kim, H.C., W.-P. Baek, and S.H. Chang (2000), "Critical Heat Flux of Water in Vertical Round Tubes at Low Pressure and Low Flow Conditions," Nuclear Engineering and Design 199:49–73.

Kirillov (1984, 1985) CHF Reproducibility Study

Kirillov et al. (1984) compared the results of a unique collaborative CHF experimental investigation performed at 10 different laboratories in the Union of Soviet Socialist Republics (U.S.S.R.). The objective of this collaboration was to compare the CHF obtained in various experimental test facilities at the same nominal conditions.

All CHF experiments were performed in tubes of Kh18N10T steel (i.e., stainless steel consisting of 18-percent chrome and 10-percent nickel) with an ID of 8 mm and a wall thickness of 2 mm. The tube lengths were 1, 3, and 6 meters. All 10 participating laboratories used tubes produced from the same batch. The table below lists the test conditions.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
2,470	7.71 8.09	0.990 6.000	6,370 18,040	494 4,154	-0.494 0.981	7 1,537	110 7,700	79.41 350.90

This CHF reproducibility exercise was performed during 1981–1983 and yielded about 2,500 experimental values of the CHF power. No precise references for the various laboratories and their results were given. Kirillov et al. (1984, 1985) referred to them as follows:

- VTI
- F.E. Dzerzhinskii, All-Union Heat Engineering Institute (FEI)
- I. Polzunov, Central Boiler-Turbine Institute (TsKTI)
- V. Kurchatov, Institute of Atomic Energy (IAE)
- Institute of Engineering Thermophysics of the Academy of Sciences of the Ukrainian SSR (ITTF)
- Special Design Office (SDO) "Gidropress"
- NIKIET
- Scientific-Production Union (SPU) "Energiya"
- Kiev Polytechnical Institute (KPI), Ukraine
- Elektrogorsk Research Station (ENIS)

The results show that the spread in CHF power was 16 to 32 percent for the 1-meter heated length and 10 percent for the 3-meter heated length. The spread in CHF on a CHF versus critical quality plot was significantly higher. Additional details of this reproducibility exercise appear in Kirillov (1997). Note that Kirillov and coworkers at the Institute of Physics and Power Engineering (IPPE) in Obninsk originally compiled a CHF database of over 14,000 data points from primarily U.S.S.R. sources (the "IPPE" database). These data were transferred to UofO around 1992.

The original Kirillov database, which Kirillov transferred to Groeneveld in the early 1990s, consisted of six data sets identified by the original experimenter. The reproducibility exercise data reported here were a subset of the original 14,000 data points from IPPE and were labeled as "Kirillov et al., 1984."

REFERENCES:

Kirillov, P.L., O.L. Peskov, and N.P. Serdun (1985), "Control Experiment on Critical Heat Transfer during Water Flow in Pipes," Soviet Atomic Energy 57:858–860, Translation from original article by Kirillov et al. in Atomnaya Energiya 57(6):422–423, December 1984.

Kirillov, P.L. (1997), Addendum and comments to the paper titled, "1995 Look-Up Table for Calculating Critical Heat Flux in Tubes," Thermal Engineering 44(10):841–850.

Kirillov Database (1992)

Kirillov and coworkers at the IPPE in Obninsk, Russia, compiled a CHF database of over 14,000 data points from primarily U.S.S.R. sources. These data were transferred to UofO around 1992. Subsequently, Groeneveld and Kirillov combined their databases, which expanded the total number of data points beyond 29,000. The combined database is referred as the "the AECL-UO-IPPE CHF database," which became the basis of the 1996 CHF LUT (Groeneveld et al., 1995).

The database that Kirillov transferred to Groeneveld consisted of six data sets that the original experimenter identified. The table below lists the original experimenters and the number of data points in each subset of Kirillov's database.

Experimenter	**Number of Data Points**
Alekseev et al. (1964)	1,108
Zenkevich (1969)	5,641
Zenkevich et al. (1971)	392
Ladislau (1978)	136
Smolin et al. (1979)	3,009
Bergelson (1980)	336
Kirillov et al. (1984)	2,470

Some data originating from the U.S.S.R. were already covered in the AECL-UO database and were removed from the Kirillov database. The subset labeled as "Kirillov et al., 1984" contains 2,470 data points that were actually obtained by other experimenters (names unknown) as their contribution to the reproducibility exercise described by Kirillov et al. (1984) and Kirillov (1997) and reported above under the section "Kirillov (1984, 1985) CHF Reproducibility Study."

REFERENCES:

Groeneveld, D.C., L.K.H. Leung, P.L. Kirillov, V.P. Bobov, I.P. Smogalev, V.N. Vinogradov, X.C. Huang, and E. Royer (1996), "The 1995 Look-Up Table for Critical Heat Flux in Tubes," Nuclear Engineering and Design 163:1–23.

Kirillov, P.L., O.L. Peskov, and N.P. Serdun (1985), "Control Experiment on Critical Heat Transfer during Water Flow in Pipes," Soviet Atomic Energy 57:858-860, Translation from original article by Kirillov et al. in Atomnaya Energiya 57(6):422–423, December 1984

Kureta (1997)

These data were extracted from Kureta's doctoral thesis (1997). The data set contains 949 data points with tubes of a small diameter under low-pressure conditions. All experimental data were obtained in a vertical test section with upflow using pure water as a test fluid. Atmospheric pressure is the exit pressure of the test sections. Details on the material of the test section or the method of CHF detection are not available. The table below lists the ranges of conditions covered by the data set.

Tube Diameter	Heated Length	L/D ratio	Pressure	Mass Flux	Local Quality	Heat Flux	Inlet Temperature
mm	mm	-	kPa	kg m^{-2} s^{-1}	-	kW m^{-2}	°C
1.0 6.0	4.0 680.0	1.0 113.3	101.3	0 19,130	-0.147 > 1.0	35.3 158,100	6.7 100.0

Note that the L/D ratio is sometimes 1, which seems experimentally very difficult to achieve. The CHF screening tests for acceptable CHF data reject very low L/D data.

REFERENCE:

Kureta, M. (1997), "A Data Set of Critical Heat Flux for Flow-Boiling of Water in Small-Diameter Tubes under Low-Pressure Conditions," Kyoto University, Kyoto, Japan, Ph.D. Thesis, Appendix A, 44 pages.

Lee (1965)

Lee (1965) experimentally investigated the effect of AFD, wall thickness, heated length, and tube diameter in his experiments. Lee's tube diameters varied from 0.364 to 0.464 inch, the wall thickness varied from 0.034 to 0.080 inch, and the heated length varied from 34 to 144 inches. Appendix II of Lee's report summarizes the tube diameter and heated length results as follows: 165 tube CHF points are tabulated, all for pressures around 1,000 psia (about 7 MPa). The quality ranges from 0.007 to 0.447, and the mass flux ranges from 1.468×10^6 to 3.017×10^6 pounds per hour per square foot.

Lee compared his results to those of Lee and Obertelli (1963) and Kearsey (1964). Appendix IV contains eight data points obtained by Lee and Obertelli (1963) under conditions similar to Lee's 1965 study; these data points are part of the dataset described separately under Lee and Obertellli (1963). Appendix V of Lee's report contains 52 CHF data points obtained from Kearsey (1964), which were also obtained under similar conditions. The reproducibility of the data is quite good, generally within 3 percent. Kearsey's data were not used for development of the 2006 CHF LUT.

Finally, Appendix VI of Lee's report tabulated his (1963) CHF data (87 CHF data points), designed to investigate the wall thickness effect. The effect varies from no effect for the longer length of 68 inches to possibly an 8-percent higher CHF for the thicker wall and for the shorter heated length (34 inches).

Only 37 CHF data points from Lee (1965) were used in the development of the 2006 CHF LUT, while 242 CHF measurements were obtained. The remainder can be used for future LUT updates or for validation of the 2006 CHF LUT. The table below lists the ranges of the Lee (1965) data used for LUT derivation.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
37	9.50	1.73 3.05	6,828 7,024	2,020 5,720	0.002 0.433	75.5 577	1,307 3,873	161 271

REFERENCES:

Lee, D.H. (1965), "An Experimental Investigation of Forced Convection Burnout in High-Pressure Water. Part III: Long Tubes with Uniform and Nonuniform Heat Flux," AEEW-R355, United Kingdom Atomic Energy Authority, Harwell, United Kingdom.

Lee, D.H., and J.D. Obertelli (1963), "An Experimental Investigation of Forced Convection Boiling in High Pressure Water," AEEW-R213, United Kingdom Atomic Energy Authority, Harwell, United Kingdom.

Kearsey, H.A. (1964), Private communication with Lee, D.H.

Lee (1966)

Lee (1966) performed several tests with larger diameter tubes (0.554, 0.862, 1.11, and 1.76 inches) at high pressures. The experimental technique was similar to that used by Lee (1965); the test section was equipped with thermocouples acting as CHF detectors. The table below lists the ranges of conditions covered by the CHF experiments.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
435	14.10 44.70	0.635 1.524	8,237 12,579	332.2 3,410.3	-0.110 0.780	60 451	870.7 3,738.2	259.80 318.09

REFERENCE:

Lee, D.H. (1966), "An Experimental Investigation of Forced Convection Burnout in High-Pressure Water. Part IV: Large Diameter Tubes at about 1,600 P.S.I.," AEEW-R479, Atomic Energy Research Establishment, Winfrith, Dorchester, Dorset, United Kingdom, November 1966, 70 pages.

Lee, D.H. (1965), "An Experimental Investigation of Forced Convection Burnout in High-Pressure Water. Part III: Long Tubes with Uniform and Nonuniform Heat Flux," AEEW-R355, United Kingdom Atomic Energy Authority, Harwell, United Kingdom.

Leung (1989)

Leung (1989) obtained these data as part of his doctoral thesis research. He did not report them in his thesis (Leung, 1994), but the thesis refers to these CHF tests, and the geometry of his thesis experiments corresponds exactly to this geometry. The table below lists the range of test conditions.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
66	5.45	2.511	5,030 9,710	1,167.6 9,938.3	0.210 0.578	6 316	656.2 3,058.3	227.85 305.33

REFERENCE:

Leung, L.K.H. (1994), "A Model for Predicting the Pressure Gradient along a Heated Channel during Flow Boiling," Ph.D. Thesis, Department of Mechanical Engineering, University of Ottawa, Ottawa, Ontario, Canada.

Leung et al. (1990)

The Leung et al. (1990) data were used to derive the 2006 CHF LUT. Because of the restricted distribution of this data, the test parameters and CHF data are not included here.

It is suspected that the data for this experiment came from the following reference, which has a restricted distribution.

REFERENCE:

Leung, L.K.H., S.T. Yin, and J. Martin (1990), "Measurements of Critical Heat Flux, Post-Dryout Pressure Drops and Wall Temperature in Tubes," COG-90-32 (also ARD-TD-227), Restricted Distribution.

Lowdermilk et al. (1958)

The purpose of this CHF experiment was to investigate the effects of flow-system characteristics on flow stability and burnout. An open-cycle or once-through flow system was chosen, and the flow was restricted upstream from the test section and discharged into a compressible volume at the exit of the test section. With this system, flow stability and burnout can be defined by determining the pressure drop across the flow restriction in addition to usual burnout variables, such as flow rate, pressure, temperature, and tube geometry.

The test sections were made of Type 347 stainless steel. Figure A-1 shows the test-section schematic with the power clamp location. The table below lists the dimensions of the test section.

Inside Diameter (mm)	Heated Length/Diameter Ratio	Unheated Length/Diameter Ratio	Wall Thickness (mm)	Wall Thickness/Inside Diameter Ratio
1.30	50, 100, 150, 200, 250	7.3	0.84	0.65
1.30	250	7.3	1.88	1.45
1.93	50, 100, 150, 200, 250	4.9	1.02	0.53
2.44	50, 100, 150, 200, 250	3.9	1.45	0.59
3.12	25, 50, 100, 150, 200, 250	3.0	1.65	0.53
3.96	25, 50, 100, 150, 200, 250	2.4	1.22	0.31
4.76	25, 50, 100, 150, 200, 250	2.0	2.37	0.50

The test sections were polished before their installation. For the majority of the runs conducted, the heated length of the test section was varied by using the 250 L/D (length-diameter) sections and by clamping the inlet electric power supply cable at the desired location along the tube length, as shown in Figure A-1. In the experimental runs using a preheater, the preheater power supply cables were connected across the length of the tube that was not being heated by the main power supply, as shown in Figure A-1.

The data shown in Tables I and II in Lowdermilk et al. (1958) should not be used in future LUT derivations/validations because, respectively, they correspond to the effect of a compressible volume and the effect of a flow restriction at the inlet—both of which were found to have a strong effect on CHF. The maximum values of the burnout heat flux were obtained for a stable flow by restricting the flow upstream from the test section. The minimum pressure drop across the restriction required to stabilize the flow increased from 5 to 100 pounds per square inch (psi) when the inlet flow velocity was increased from 0.5 to 40 feet per second.

In addition, a compressible volume introduced in the flow system between the flow restriction and the inlet of the test section resulted in unsteady flow during burnout. The flow fluctuations increased, and the burnout heat flux decreased with an increase in the compressible volume.

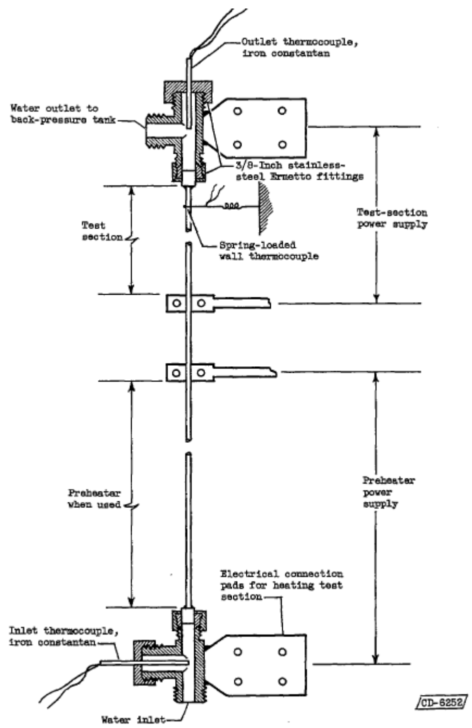

Figure A-1 Test section Details in Lowdermilk et al. (1958)

The table below lists the range of test conditions suitable for LUT derivation.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
470	4.00 4.80	0.119 0.991	100	27.2 4,865.5	0.030 1.236	317 331	167 9,525	20.91 24.24

For the 2006 LUT derivation, only 112 CHF data points were used—the data with small diameters (D < 4 mm) and short lengths (L/D < 50) were excluded.

REFERENCE:

Lowdermilk, W.H., C.D. Lanzo, and B.L. Siegel (1958), "Investigation of Boiling Burnout and Flow Stability for Water Flowing in Tubes," NACA-TN-4382, National Advisory Committee for Aeronautics (NACA), Cleveland, OH, September 1958, 52 pages.

Matzner et al. (1965)

Matzner et al. (1965) performed CHF experiments at Columbia University on an Inconel tube with vertical upflow. The test section was equipped with thermocouples at the downstream end to detect CHF occurrence. As extra protection, the test section was also used as one leg of a Wheatstone bridge—an imbalance in the bridge circuit was indicative of CHF occurrence. The table below lists the ranges of conditions covered by the CHF experiments.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
99	10.20	2.438 4.877	6,893	1,193.3 9,559.8	0.008 0.693	48 1,183	643.5 4,041	65.61 275.82

REFERENCE:

Matzner, B., E.O. Moeck, J.E. Casterline, and G.A. Wikhammer (1965), "Critical Heat Flux in Long Tubes at 1,000 psi with and without Swirl Promoters," Paper 65-WA/HT-30, AECL-2446, Proceedings of the American Society of Mechanical Engineers, 16 pages.

Mayinger et al. (1966)

The purpose of this CHF experiment was to study the effects of upstream history and the inlet conditions, as well as the L/D ratio of the test channel. The tests were made at pressures of 70 to 140 kilogram-force per square centimeter using internally cooled tubes with diameters varying from 0.7 to 1.5 cm. The conditions at the test channel inlets covered mass flows between 100 and 350 grams per square centimeter per second using either a subcooled inlet or two-phase inlet (up to 20 percent).

The two types of burnout observed are completely different in their physical appearance. One type is characterized by the occurrence of fluctuations in the pressure and mass flow shortly before film boiling starts; this was designated as "pulsating burnout." The other type shows a hydrodynamically completely stable behavior until film boiling suddenly occurs. Pulsating burnout (observed only at subcooled boiling conditions) was found to lead to critical heat flux levels 20 to 50 percent below those obtained with hydrodynamically stable flow. An even greater influence on the CHF was obtained by a reduction of the L/D ratio. With very short test sections with an L/D ratio of 5 to 10, the critical heat flux is 4 to 5 times the value obtained with long test channels with an L/D ratio of 80 to 100. The table below lists the ranges of conditions covered by the CHF experiments.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
128	7.00	0.560 0.980	1,925 10,244	2,233 3,734	0.098 0.405	-239 314	924 5,618	233.28 310.09

REFERENCE:

Mayinger, F., O. Schad, and E. Weiss (1966), "Untersuchung der kritischen Heizflachenbelastung (Burnout) bei sieden dem Wasser (Translation: Investigation into the Critical Heat Flux in Boiling)," 09.03.01, Maschinenfabrik Augsburg-Nurnberg AG, Munich, Germany, May 1966, 265 pages.

Nariai et al. (1987)

The Nariai et al. (1987) data were obtained in small diameter tubes (1, 2, and 3 mm) under high flow and at near-atmospheric pressure. This paper does not report the data, which were obtained separately. Only seven data points were used for the 2006 CHF LUT derivation. The table below lists the ranges of conditions covered by the CHF experiments.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
93	1.00 3.00	0.009 0.101	100	6,710 20,910	-0.134 0.007	149.5 353	4,647 69,990	15.4 64

REFERENCE:

Nariai, H., F. Inasaka, and T. Shimura (1987), "Critical Heat Flux of Subcooled Flow Boiling in Narrow Tubes," in the Proceedings of the 1987 American Society of Mechanical Engineers/Japan Society of Mechanical Engineers Thermal Engineering Joint Conference, Honolulu, HI, March 22–27, 1987, P.J. Marto and I. Tanasawa (Eds.), American Society of Mechanical Engineers, New York, NY, Volume 5, pp. 455–462.

Nariai CHF Data Set from Celata (2001)

The data were contained in 2001 from a personal communication from G.P. Celata to UofO. Celata had received data directly from Nariai. This data set contains 14 data points. Details of the experiment are not known. The table below lists the ranges of flow parameters.

Tube Diameter	Heated Length	L_h/D ratio	Pressure	Mass Flux	Critical Quality	Heat Flux	Inlet Temperature
mm	m	-	kPa	kg m^{-2} s^{-1}	-	kW m^{-2}	°C
6.0	0.100	16.6	100.0 1,500.0	4,590.0 8,690.0	-0.2596 0.0577	8,500.0 22,100.0	38.3 44.7

REFERENCE:

Personal communication between G.P. Celata and Professor S.C. Cheng, University of Ottawa, Ottawa, Ontario, Canada, April 22, 1993.

Nguyen and Yin (1975)

CHF tests were performed in an Inconel 600 tube with an ID of 0.496 inch. Measurements were obtained with the test section in both the vertical and horizontal positions (this paper reports only the vertical tube CHF data). CHF was detected using Type K thermocouples. The table below lists the ranges of conditions covered by the CHF experiments.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
56	12.60	2.438 4.877	6,645 8,401	929.6 3,838.4	0.216 0.738	52 413	677 2,023.7	225.06 276.81

REFERENCE:

Nguyen, D.M., and S.T. Yin (1975), "An Experimental Investigation of Water Critical Heat Flux in a Tubular Channel in Both Horizontal and Vertical Attitudes," Technical Memorandum CWTM-013-HT, Westinghouse Canada Limited, Toronto, Canada, December 1975, 39 pages.

Olekhnovitch (1997)

The electronic copy of this data set was obtained from private communications between D.C. Groeneveld and A. Olekhnovitch. Olekhnovitch et al. (1999) and Olekhnovitch (1997) later described details of the experiment for the same data set. This data set contains 479 data points. The test sections consisted of vertical, uniformly heated tubes through which the water flowed vertically upwards. The Inconel 600 tubes had a wall thickness of either 1 mm or 2 mm. To detect the dryout occurrence, 30 chromel-alumel thermocouples were spot welded on the surface of the tube. The table below lists the ranges of flow parameters.

Tube Diameter	Heated Length	L_h/D ratio	Pressure	Mass Flux	Critical Quality	Heat Flux	Inlet Temperature
mm	m	-	kPa	kg m^{-2} s^{-1}	-	kW m^{-2}	°C
8.0	0.750 3.500	93.8 437.5	507.0 4,036.0	977.0 6,122.0	0.0460 0.7610	523.0 5,550.0	47.2 244.5

REFERENCES:

Olekhnovitch, A. (1997), "Etude de Flux de Chaleur Critique a des Pressions Faibles," Universite de Montreal, Montreal, Quebec, Canada, Ph.D. Thesis, October 1997, 599 pages.

Olekhnovitch, A., A. Teyssedou, A. Tapucu, P. Champagne, and D.C. Groeneveld (1999), "Critical Heat Flux in Vertical Tube at Low and Medium Pressures. Part I: Experimental Results." Nuclear Engineering and Design 193:73–89

Olekhnovitch, A., A. Teyssedou, and P. Tye (1999), "Critical Heat Flux in Vertical Tube at Low and Medium Pressures. Part II: New Data Presentation." Nuclear Engineering and Design 193:91–103.

Pabisz and Bergles (1996)

Pabisz and Bergles (1996) investigated the effect of additives on CHF. The data reported here are the 10 reference tests that measured the CHF in a directly heated tube; six of these tests were used as a database for the derivation of the 2006 CHF LUT. The tubes were made of stainless steel, and CHF was defined as the heat flux where actual burnout (i.e., tube failure) occurred. The table below lists the ranges of conditions covered by the CHF experiments.

Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
4.40 6.20	0.11 0.154	627 1,284	2,417 4,994	-0.196 -0.133	567 698	7,370 13,880	15.3 46

REFERENCE:

Pabisz, R.A., Jr., and A.E. Bergles (1996), "Enhancement of Critical Heat Flux in Subcooled Flow Boiling of Water by Use of a Volatile Additive," in the Proceedings of the American Society of Mechanical Engineers Heat Transfer Division (HTD), Presented at the 1996 International Mechanical Engineering Congress and Exposition, Atlanta, GA, November 17–22, 1996, HTD-Volume 334, Volume 3, pp. 305–312.

Peterlongo et al. (1964)

Peterlongo et al. (1964) obtained data for upward flow of steam-water mixtures in round vertical tubes. The data set contains 351 data points without obstacles and additional data points with internal obstacles. The test sections were seamless AISI Type 304 stainless steel tubes with a length of 4.996 meters. CHF was detected by nickel-nickel/chrome thermocouples attached to the heated tube. For subcooled or low-quality conditions, CHF was of the departure from nucleate boiling type, characterized by a sharp increase in temperature for a small increase in heat flux. However, for higher qualities, the CHF was more of a slow dryout type. Here, the wall temperature rise was plotted against heat flux (i.e., the boiling curve), and CHF was defined as a sharp decrease in the slope of a heat flux versus wall temperature plot. The table below lists the ranges of test conditions covered by the tests.

Tube Diameter	Tube Length	Heated Length	Pressure	Mass Flux	Local Quality	Heat Flux	Inlet Temperature
mm	m	m	kPa	kg m^{-2} s^{-1}	-	kW m^{-2}	°C
15.1 15.2	4.996	1.6 4.116	4,982 6,551	1,080 3,910	-0.023 0.608	895 4,115	26.15 280.47

REFERENCE:

Peterlongo, G., R. Ravetta, B. Riva, L. Rubiera, and F.A. Tacconi (1964), "Large Scale Experiments on Heat Transfer and Hydrodynamics with Steam—Water Mixtures: Further Critical Power and Pressure Drop Measurements in Round Vertical Tubes with and without Internal Obstacles," R-122, Centro Informazioni Studi Esperienze (CISE), Segrate, Milan, Italy.

Rudzinski et al. (1999)

This experiment was performed as part of an investigation to examine the effect of flow, pressure, and heat flux transients on CHF. Only the reference steady-state tests are reported here. Because of the restricted distribution of this data, the test parameters and CHF data are not included here.

REFERENCE:

Rudzinski, K.F., D.C. Groeneveld, and S. Doerffer (1999), "Analysis of the Flow Transient CHF and Rewetting Data Obtained in an 8 mm Tube," FFC-FCT-65, COG-96-510, Atomic Energy of Canada Limited, Chalk River, Ontario, Canada, February 1999, 142 pages. Restricted Distribution.

Shan (2005)

Shan (2005) was assisting in the UofO LUT development work before 2005. He identified some CHF tube data that were labeled as "Col-U" (Columbia University). This data set was based on both 8-mm and 15.82-mm-ID tube test sections. No source for these data could be found. The table below lists the ranges of conditions covered by the CHF experiments used in the derivation of the 2006 LUT.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Heat Flux
Number	Mm	m	kPa	kg m^{-2} s^{-1}	-	kW m^{-2}
24	8.00 15.82	1.00 2.4384	317 14,808	572 8,015	-0.022 0.422	819.5 5,691

Smolin et al. (1962)

The Smolin et al. (1962) reference for these data does not seem to correspond to the experimental data because it refers to 8-mm data that were obtained only at P = 150 atmospheres. The 1962 experiment was performed in a 2.6-meter-long heated test section where the flow was slowly reduced for a fixed heat flux until a temperature rise of about 10 to 15 degrees Kelvin was detected by the thermocouples welded to the test-section wall near the downstream end of the heated length. (See also the reference to Smolin's work in Zenkevich (1974)). The table below lists the test conditions.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
number	Mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
369	3.84 10.80	0.776 4.000	7,840 19,610	498 7,556	-0.132 0.795	5 1,329	230 5,652	140.35 350.39

REFERENCES:

Smolin, V.N., V.K. Polyakov, and V.I. Esikov (1962), "On the Heat Transfer Crisis in Steam-Generating Pipes," Soviet Journal of Atomic Energy 13:968–972, Translation from Atomnaya Energiya 13(4):360–364.

Groeneveld, D.C., L.K.H. Leung, P.L. Kirillov, V.P. Bobov, I.P. Smogalev, V.N. Vinogradov, X.C. Huang, and E. Royer (1996), "The 1995 Look-Up Table for Critical Heat Flux in Tubes," Nuclear Engineering and Design 163:1–23.

Smolin (1979)

The Smolin (1979) data came from the database transferred by Kirillov to UofO around 1992 and described above under the section titled, "Kirillov Database (1992)." No documentation was provided. Smolin's experiment may have been similar to an earlier experiment by Smolin, as reported in Smolin (1962). The table below lists the test conditions.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
2,987	3.84 16.00	0.690 6.050	2,940 17,710	490 7,672	-0.136 0.789	4 1,362	245 5,626	72.72 351.65

REFERENCE:

Smolin, V.N., V.K. Polyakov, and V.I. Esikov (1962), "On the Heat Transfer Crisis in Steam-Generating Pipes," Soviet Journal of Atomic Energy 13:968–972, Translation from Atomnaya Energiya 13(4):360–364.

Snoek (1988)

The Snoek (1988) experiment was designed to investigate the effect of subchannel shape on CHF. The original report is proprietary to AECL and not available to the public, so the test parameters and CHF data are not included here.

REFERENCE:

Snoek, C.W. (1988), "Comparison of the Critical Heat Flux in Interconnected Subchannels of Different Geometry," Internal Report CRNL-4231, CANDEV-88-23, Atomic Energy of Canada Limited, Chalk River, Ontario, Canada, December 1988.

Soderquist (1994)

The electronic copy of this large data set was obtained directly from the author, B. Soderquist, from the Department of Nuclear Reactor Engineering, Royal Institute of Technology, Stockholm, Sweden, and was also made available at an anonymous FTP site. The electronic version contains 1,485 data points. Subsequently, a printed copy of the data and experimental details were received as well. It refers to 1,485 data points that were obtained although the printed copy only contains 1,410 data points. Data points 1411–1485 are missing from the printed version; however, because the first 1,410 data points are the same as in the electronic copy, it is believed that the data points 1411–1485 were obtained in the same manner. The data set also contains 110 CHF data points with quality greater than 1, an obvious impossibility. These $X > 1.0$ data were all obtained at low flows ($G \sim 250$ kg m^{-2} s^{-1}). This suggests that the low-flow data may not be reliable, even though the author quotes errors of 1 percent in pressure, 0.8 percent in mass flux, and 0.5 percent in power. The heat balances for the single-phase flow were within 1 percent. The table below lists the ranges of parameters.

Tube Diameter	Heated Length	L_h/D ratio	Pressure	Mass Flux	Critical Quality	Heat Flux	Inlet Temperature
mm	m	-	kPa	kg m^{-2} s^{-1}	-	kW m^{-2}	°C
7.98 8.11	1.000 6.000	123.3 751.9	970.0 20,120.0	243.0 6,085.0	-0.169 1.00	50.0 3,879.0	118.3 356.9

The test-section material was stainless steel. Because stainless steel has a high-temperature coefficient of resistance compared to Inconel, the true heat flux at the downstream end will be higher than the reported average heat flux.

REFERENCE:

Soderquist, B. (1994), "Swedish CHF Data," Department of Nuclear Reactor Engineering, Royal Institute of Technology, Stockholm, Sweden, Personal communication with D.C. Groeneveld (received from Soderquist in March 1994).

Swenson et al. (1962)

Swenson et al. (1962) obtained the data. The data set contains 25 data points with uniform heat flux distribution and other data points with three nonuniform axial heat flux distributions. The test sections were seamless AISI Type 304 stainless steel tubes with a length of 2.9464 meters (116 inches) and an ID that varied from 10.44 to 11.33 mm (0.411 to 0.446 inch). The tubes are installed vertically with the flow upward. The intermediate 1.8288-meter (72-inch) length was heated electrically. The table below lists the ranges of conditions covered by the data set.

Tube Diameter	Heated Length	Pressure	Mass Flux	Local Quality	Heat Flux	Inlet Temperature
mm	m	kPa	kg m^{-2} s^{-1}	-	kW m^{-2}	°C
10.44 10.54	1.8288	13,790	678.7 1,764.7	0.178 0.502	586.83 1,063.24	231.4 329.4

REFERENCE:

Swenson, H.S., J.R. Carver, and C.R. Kakarala (1962), "The Influence of Axial Heat-Flux Distribution on the Departure from Nuclear Boiling in a Water-Cooled Tube," Paper No. 62-WA-297, American Society of Mechanical Engineers, New York, NY, 15 pages.

Tian (1994)

The reference or documentation could not be located. The data are from a private communication.

Tong (1964)

No documentation could be found for this set of data. The table below lists the ranges of conditions covered by the CHF data set.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
266	6.22 12.90	0.380 3.660	5,171 13,790	678 14,002	0.002 0.502	5 1,060	587 6,139	263.94 330.85

REFERENCE:

No reference.

Waters et al. (1965)

This data set contains 38 data points. The test section consisted of a vertical, uniformly heated Inconel tube with a 4.8-mm wall thickness through which the water flowed upwards. The 20 thermocouples spot welded to the outer surface of the tube at 30.5-cm axial intervals were used as burnout detectors. This experiment showed that the initial CHF occurrence with a uniform AFD can occur at upstream locations, especially at high flows. The dryout quality, the inlet temperature, and the inlet subcooling enthalpy have been calculated by the enthalpies given in the papers. The table below lists the ranges of flow parameters.

Tube Diameter	Heated Length	Pressure	Mass Flux	Inlet Quality	Heat Flux	Inlet Temperature
mm	m	kPa	kg m^{-2} s^{-1}	-	kW m^{-2}	°C
11.2	3.658	6,894.76 10,342.14	6,645.53 9,547.86	-0.0335 0.3218	2,016.92 5,388.95	86.93 313.48

REFERENCE:

Waters, E.D., J.K. Anderson, W.L. Thorne, and J.M. Batch (1965), "Experimental Observations of Upstream Boiling Burnout," Chemical Engineering Progress Symposium Series 61(57):230–237.

Whittle and Forgan (1967)

This data set contains 59 data points. The vertical test sections consisted of a rectangular channel and a single, uniformly heated round tube through which subcooled water flowed upwards. The distinctiveness of this test procedure was that, for a fixed power, the flow rate was reduced from a maximum value while the test-section pressure drop was monitored carefully. The flow rate that corresponded to the minimal pressure drop is related to the CHF occurrence. The table below lists the ranges of flow parameters.

Tube Diameter	Heated Length	Pressure	Mass Flux	Inlet Quality	Heat Flux	Inlet Temperature
mm	M	kPa	kg m^{-2} s^{-1}	-	kW m^{-2}	°C
6.45	0.4064 0.6096	117.2 172.4	1,643.5 9,137	-0.03105 -0.00879	660 3,480	35 75

REFERENCE:

The reference to this data set may be in the following article:

Whittle, R.H., and R. Forgan (1967), "A Correlation for the Minima in the Pressure Drop versus Flow-Rate Curves for Subcooled Water Flowing in Narrow Heated Channels," Nuclear Engineering and Design 6:89–99.

Williams and Baus (1980) (CHF data set from the Zummo database)

The electronic copy of this data set was extracted from the Zummo CHF database. The database was obtained in personal communication between G. Zummo, K. Mishima, and Y. Guo, and D.C. Groeneveld. The original paper by Williams and Baus (1980) became available later and confirms the validity of the data. This data set contains 129 data points. All experimental data are for a vertical tube with upflow using water as a test fluid. The test section was made of Type 304 stainless steel. The table below lists the ranges of parameters for this data set.

Tube Diameter	Heated Length	L_h/D ratio	Pressure	Mass Flux	Local Quality	Heat Flux	Inlet Temperature
mm	m	-	kPa	kg m^{-2} s^{-1}	-	kW m^{-2}	°C
9.5	1.840	193.6842	2,758 15,169	324 4,662	-0.025 0.929	388 4,073	90 315

REFERENCE:

Williams, C.L., and S.G. Baus (1980) "Critical Heat Flux Experiments in a Circular Tube with Heavy Water and Light Water," WAPD-TM-1462, Bettis Atomic Power Laboratory, West Mifflin, PA, May 1980.

Yin et al. (1988)

Yin et al. (1988) performed CHF tests in a 13.4-mm-ID tube (with a wall thickness of 1.24 mm) made of Inconel 600 using only one nominal mass flux of 2,030 kg m^{-2} s^{-1}. The test section was equipped with multiple chromel-alumel thermocouples that served as dryout detectors. The table below lists the ranges of conditions covered by the CHF experiments.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
287	13.40	3.658	1,028 21,197	1,938.9 2,081.6	0.075 0.431	0 493	583.3 1,863.7	128.42 358.41

REFERENCE:

Yin, S.T., T.-J. Liu, Y.-D. Huang, and R.M. Tain (1988), "Measurements of Critical Heat Flux in Forced Flow at Pressures Up to the Vicinity of the Critical Point of Water," in the Proceedings of the 1988 National Heat Transfer Conference, Houston, TX, July 24–27, 1988, Volume 2, pp. 501–506.

Zenkevich (1971)

The data were attributed to Kirillov's database (see the section "Kirillov Database (1992)") that was transferred to the UofO in the early 1990s). The 392 CHF were used for the 2006 LUT derivation. Details of the test section and the method of CHF detection are not available. The table below lists the ranges of conditions covered by the CHF data set.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
number	Mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
392	7.80 8.05	7.000 20.000	6,860 17,650	1,008 2,783	0.262 0.876	18 1,549	47 1,283	81.96 352.22

REFERENCE:

There is no direct reference; the only indirect reference is from Kirillov's 1992 CHF database.

Zenkevich, Peskov, and Subbotin (1964) CHF Data Set

This data set contains 67 points. The test section consisted of tubes of 1Cr18Ni9Ti stainless steel with uniformly heated walls 0.75 to 1.5 mm thick. The table below lists the ranges of flow parameters.

Tube Diameter	Heated Length	Pressure	Mass Flux	Inlet Quality	Heat Flux	Inlet Temperature
Mm	mm	kPa	kg m^{-2} s^{-1}	-	kW m^{-2}	°C
6.8, 8, and 10	100 666	3,924 9,810	550 6,444.5	-0.01971 0.66008	5,000 9,710	211.02 286.39

Only one point was used for the 2006 CHF LUT derivation.

REFERENCE:

Zenkevich, B.A., O.L. Peskov, and N.D. Subbotin (1964), "A Study of Critical Heat Flux Densities for Tubular Fuel Elements at Atomic Power Stations," Teploenergetika (in Russian) 11(6):20–22, Thermal Engineering (English translation) 11(6):23–25.

Zenkevich CHF data (1969)

A reference for these data could not be found. They were included in the data compilation of Kirillov that was transferred to the UofO in the early 1990s (see the section "Kirillov Database (1992)"). Details of the test section and the method of CHF detection are not available. The table below lists the ranges of conditions covered by this CHF data set.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux
number	mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}
5,595	3.99 15.10	0.250 6.000	5,880 19,610	498 9,876	-1.652 0.964	2 1,644	136 14,760

Zenkevich (1974)

The translation of Zenkevich (1974) is a very large report (over 400 pages) and contains about 7,000 CHF data points, many of which were obtained in uniformly heated tubes; the author obtained about 650 of these data points. This valuable resource provides an excellent summary of data obtained in the U.S.S.R. and elsewhere. The translation also includes additional data sets obtained by seven different authors. With the exception of the Smolin et al. (1962, 1964, 1965) data, these additional data were known and have already been tabulated. The odd-numbered tables between Tables 16 and 35 contain CHF data obtained in tubes but with a nonuniform AFD and should be ignored. Table 1 provides the ranges of conditions covered by 31 pre-1974 CHF data known by Zenkevich, some of which had a two-phase inlet. The table below lists the ranges of conditions covered by Zenkevich's tabulation of the CHF data points, which were obtained in uniformly heated tubes and used for the 2006 LUT derivation.

No. of Data Points	Tube Diameter	Heated Length	Pressure	Mass Flux	Critical Quality	Inlet Subcooling	Heat Flux	Inlet Temperature
number	Mm	m	kPa	kg m^{-2} s^{-1}	-	kJ kg^{-1}	kW m^{-2}	°C
823	4.80 12.60	1.000 6.000	5,890 19,620	497.2 6,694.4	-0.221 0.969	5 1,381	230 4,740	96.70 358.24

A difference exists between the number of data points in the report attributed to Zenkevich (about 650) and the number of data points attributed to Zenkevich in the database used to derive the 2006 LUT (823).

REFERENCES:

Zenkevich, A., O.L. Peskov, G.A. Petrishcheva, N.D. Sergeev, and V.I. Subbotin. (1974), "Analysis and Generalization of Experimental Data on Heat Transfer Crisis Associated with Forced Convection of Cooling Water in Tubes," AECL-Tr-Misc.-304, Atomic Energy of Canada Limited, Chalk River, Ontario, Canada.

Smolin, V.N., V.K. Polyakov, and V.I. Esikov (1962), "Heat-Transfer Crisis in a Steam-Generating Tube," Atomnaya Energiya 14(4):360–364.

Smolin, V.N., V.K. Polyakov, and V.I. Esikov (1964), "Experimental Investigation of Heat-Transfer Crisis," Atomnaya Energiya 16(5):417–423.

Smolin, V.N., V.K. Polyakov, and V.I. Esikov (1965), Trudy (Proceedings) of the NPO Tsentralny kotloturbinny institut (TsKTI), No. 58.

APPENDIX B

REFERENCES TO CRITICAL HEAT FLUX DATA SETS FOR WATER-COOLED TUBES

B-1 References to Critical Heat Flux Data Sets Used To Derive the 2006 Critical Heat Flux Lookup Table

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APPENDIX C

COMPLETE 2006 CRITICAL HEAT FLUX LOOKUP TABLE

The following pages contain the complete 2006 critical heat flux (CHF) lookup table, which gives the CHF in kilowatts per square meter. Section 6.2 describes the table shading that characterizes the CHF uncertainty.

P	G	X																					
kPa	kg/m^2/s	-0.50	-0.40	-0.30	-0.20	-0.15	-0.10	-0.05	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.60	0.70	0.80	0.90	1.0
100	0	8111	7252	6302	4802	4086	3057	1990	1142	637	415	284	223	188	165	152	142	133	123	114	110	96	55	0
100	50	8317	7271	6326	5035	4236	3453	2420	1570	1011	784	641	587	553	531	475	443	419	387	347	277	239	204	0
100	100	8390	7295	6371	5322	4586	3640	2942	2103	1558	1275	1013	885	847	811	789	758	745	715	700	600	459	359	0
100	300	10698	9288	7795	6020	5009	3865	3196	2479	1961	1707	1317	1177	1172	1159	1150	1100	1085	1041	1031	675	517	366	0
100	500	12882	10946	9224	6791	5348	3938	3369	2685	2087	1808	1412	1347	1311	1303	1282	1260	1212	1193	1071	605	450	295	0
100	750	16982	14405	11641	7496	5662	4234	3471	2780	2229	1970	1649	1606	1591	1563	1510	1495	1400	1280	595	415	243	206	0
100	1000	19441	16278	13255	8232	5971	4495	3533	3012	2653	2349	2070	2000	1980	1930	1715	1550	1359	1165	503	322	172	105	0
100	1500	22781	19225	15465	9100	6603	5358	3741	3524	3166	2917	2635	2572	2467	2378	1908	1350	1005	815	302	210	126	51	0
100	2000	25268	21321	17143	9141	7059	6036	4074	3855	3556	3402	3167	2986	2720	2549	1696	1105	805	595	247	105	87	39	0
100	2500	28026	23599	18346	9503	7506	6516	4502	4047	3852	3599	3228	3019	2676	2458	1148	956	708	485	290	120	46	22	0
100	3000	30294	25465	19383	9779	8063	7088	4826	4182	3976	3389	2968	2706	2369	1829	940	846	665	532	302	159	55	20	0
100	3500	32227	27043	21068	10156	8518	7302	5113	4384	4106	3196	2769	2557	2311	1729	1158	891	817	670	402	210	75	28	0
100	4000	33928	28471	22722	10512	8728	7528	5582	4709	4228	3119	2736	2504	2282	1850	1470	1160	1030	823	475	248	96	38	0
100	4500	35406	29774	23890	10945	9088	8067	6267	5013	4272	3287	2769	2541	2304	1972	1718	1405	1185	969	585	289	129	61	0
100	5000	36808	30988	24979	11185	9592	8576	6748	5113	4342	3410	2890	2629	2355	2066	1779	1498	1247	1030	647	347	167	81	0
100	5500	38232	32141	25791	11929	10084	8940	6867	5175	4389	3465	2954	2680	2406	2128	1848	1595	1334	1118	729	409	206	101	0
100	6000	39525	33222	26637	13026	10396	9347	6919	5241	4423	3580	2921	2681	2447	2170	1908	1651	1418	1204	807	468	244	121	0
100	6500	40727	34244	27480	14371	10748	9701	6995	5295	4491	3620	2918	2694	2477	2209	1965	1719	1493	1281	878	523	282	142	0
100	7000	41950	35224	28165	15045	11091	10522	7062	5370	4513	3668	2958	2724	2501	2247	2013	1780	1559	1349	943	576	319	162	0
100	7500	43448	36075	28604	15822	11538	10726	7087	5381	4585	3699	2996	2751	2526	2285	2060	1838	1622	1414	1000	615	347	180	0
100	8000	44338	36803	29089	16599	12085	10900	7313	5392	4689	3780	3031	2778	2553	2320	2103	1890	1679	1473	1054	651	371	196	0
300	0	8027	7043	6206	4761	4106	3131	2483	1374	883	606	420	313	248	205	180	165	148	141	135	131	125	67	0
300	50	8153	7058	6287	5304	4564	3729	2847	2071	1587	1315	1052	871	709	599	516	499	457	389	372	362	274	207	0
300	100	8418	7315	6499	5509	4883	4013	3238	2638	2150	1869	1528	1373	1262	1183	1127	1065	1057	1033	902	691	502	394	0
300	300	10397	9094	7805	6085	5320	4107	3429	3011	2617	2263	1862	1657	1614	1576	1513	1480	1446	1403	1193	722	572	419	0
300	500	12787	10894	9193	6962	5664	4134	3563	3285	2821	2405	2001	1832	1688	1663	1610	1610	1520	1504	1112	616	452	297	0
300	750	16084	13658	11132	7493	5853	4282	3743	3512	2987	2538	2062	1868	1698	1676	1636	1598	1447	1300	656	440	253	207	0
300	1000	17866	15378	12753	8194	6038	4572	3898	3610	3224	2791	2450	2230	2070	1990	1805	1570	1369	1173	523	334	184	112	0
300	1500	21559	18208	14718	9252	7091	6091	4818	4243	3557	3134	2981	2720	2658	2491	2042	1365	1016	813	308	210	130	57	0
300	2000	23993	20257	16367	10134	8179	6790	5171	4462	3759	3490	3410	3232	2894	2672	1803	1108	822	599	254	118	88	41	0
300	2500	26215	22280	18013	10477	8534	7134	5245	4519	3951	3681	3444	3248	2846	2521	1168	981	732	488	292	132	47	23	0
300	3000	27747	23975	19028	10840	8691	7393	5326	4551	4081	3502	3082	2977	2523	1868	945	852	681	534	304	161	56	21	0
300	3500	29254	25440	20427	10948	8793	7585	5600	4681	4195	3283	2967	2695	2389	1788	1170	895	820	675	410	226	76	29	0
300	4000	30763	26771	21520	11006	8997	8017	6253	5184	4271	3344	2951	2648	2383	1960	1500	1170	1050	850	499	264	97	39	0
300	4500	32150	27994	22599	11137	9388	8517	6725	5594	4329	3504	2981	2677	2408	2094	1746	1423	1228	998	600	304	126	59	0
300	5000	33465	29133	23700	11600	9705	8845	7103	6052	4369	3655	3048	2739	2449	2139	1843	1542	1289	1061	665	358	165	80	0

P	G	X																						
kPa	kg/m²/s	-0.50	-0.40	-0.30	-0.20	-0.15	-0.10	-0.05	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.60	0.70	0.80	0.90	1.0
300	5500	34919	30223	24325	12512	10147	9115	7281	6122	4427	3720	3070	2776	2501	2200	1881	1636	1377	1153	748	418	206	100	0
300	6000	36122	31241	25169	13522	10870	9576	7398	6323	4481	3685	3104	2773	2543	2247	1942	1708	1462	1241	828	476	244	121	0
300	6500	37231	32198	25960	14708	11330	10024	7446	6440	4571	3705	3123	2783	2578	2288	2004	1783	1543	1320	902	532	268	142	0
300	7000	38099	33093	26558	15513	11759	10532	7599	6469	4650	3772	3155	2812	2605	2327	2037	1844	1611	1391	970	586	303	150	0
300	7500	38989	34027	27283	16123	12062	10765	7689	6500	4702	3784	3221	2839	2625	2361	2095	1898	1673	1456	1029	627	331	166	0
300	8000	39744	34510	27900	16757	12891	11128	7784	6544	4760	3892	3228	2867	2649	2395	2126	1946	1728	1514	1083	664	356	181	0
500	0	7743	6834	5910	4720	4136	3342	2518	1607	1129	798	557	404	308	245	209	188	163	159	157	156	137	105	0
500	50	7983	7004	6274	5355	4711	3853	2989	2170	1731	1344	1119	958	852	775	684	556	495	465	407	395	282	235	0
500	100	8478	7421	6632	5627	5080	4057	3317	2754	2270	1988	1704	1399	1316	1229	1188	1122	1116	1109	940	711	523	417	0
500	300	10280	8983	7804	6235	5491	4193	3498	3165	2835	2537	2243	2028	1826	1647	1611	1545	1503	1464	1255	749	592	449	0
500	500	12694	10885	9073	7008	5780	4281	3671	3339	3157	2811	2462	2253	1933	1711	1651	1630	1534	1506	1177	676	476	300	0
500	750	15186	12992	10624	7610	5957	4356	3855	3630	3442	2994	2680	2379	1982	1740	1699	1615	1469	1307	684	503	274	209	0
500	1000	17460	14778	12051	8057	6145	4629	4062	3870	3684	3304	3109	2885	2613	2251	1927	1599	1399	1179	540	362	186	119	0
500	1500	20438	17191	13972	9365	7340	6298	5248	4711	4048	3594	3491	3278	3149	2774	2123	1382	1056	833	310	215	134	65	0
500	2000	22719	19293	15591	10327	8310	7309	5675	5017	4215	3772	3693	3578	3169	2795	1850	1115	832	603	260	132	89	43	0
500	2500	25104	20961	17081	10751	8703	7675	5987	5151	4435	3863	3759	3478	3017	2647	1176	1009	780	492	296	145	48	24	0
500	3000	26621	22486	18273	11002	8920	8034	6194	5168	4595	3955	3690	3216	2761	1905	948	862	698	560	306	163	58	22	0
500	3500	28248	23838	19186	11141	9008	8154	6399	5384	4757	3992	3489	3066	2723	1856	1201	899	825	681	420	229	77	30	0
500	4000	29719	25071	20019	11201	9267	8238	6955	5858	4922	4029	3355	2991	2692	2090	1540	1180	1060	870	532	271	98	39	0
500	4500	31075	26215	20508	11429	9919	8968	7201	6212	5083	4098	3257	2958	2663	2204	1776	1437	1240	1003	612	315	124	54	0
500	5000	32376	27279	21190	11913	10245	9208	7321	6399	5162	4132	3186	2907	2639	2230	1858	1551	1310	1085	693	368	153	70	0
500	5500	33684	28306	22359	12695	10581	9306	7407	6209	5291	4141	3175	2896	2637	2259	1927	1651	1401	1178	772	423	186	86	0
500	6000	34756	29261	23302	14018	11114	9598	7526	6332	5399	4190	3180	2913	2652	2287	1985	1728	1482	1263	850	478	220	103	0
500	6500	35781	30153	24141	14945	11567	9948	7751	6496	5481	4230	3246	2935	2666	2319	2029	1797	1560	1342	927	534	254	121	0
500	7000	36804	30962	24952	15581	12151	10333	8027	6828	5588	4307	3294	2939	2682	2361	2077	1864	1632	1416	997	588	288	139	0
500	7500	38036	31979	25663	16185	12686	10753	8176	6845	5700	4370	3351	2947	2697	2398	2127	1918	1695	1480	1060	631	315	153	0
500	8000	39197	33017	26712	17016	13200	11107	8256	6896	5794	4485	3389	3069	2734	2442	2177	1967	1751	1540	1120	672	342	166	0
1000	0	7347	6383	5570	4657	4175	3535	2776	2159	1820	1320	940	678	492	377	318	291	269	254	231	220	193	145	0
1000	50	7700	6956	6204	5406	4891	4169	3412	2702	2473	1966	1607	1351	1179	1068	933	770	723	706	586	522	369	282	0
1000	100	8581	7702	6906	5824	5173	4600	4000	3609	3069	2549	2380	2216	2087	1949	1798	1700	1652	1541	1280	1078	708	501	0
1000	300	10093	8830	7796	6476	5710	4793	4140	4013	3901	3685	3471	3372	3276	3172	2993	2871	2766	2594	1727	1302	815	514	0
1000	500	12148	10478	8703	7200	6004	4837	4259	4124	4063	3995	3980	3953	3938	3790	3678	3579	3537	3445	1564	1067	649	377	0
1000	750	14675	12510	10033	7775	6255	4896	4378	4337	4228	4200	4162	4083	3997	3851	3810	3473	3291	3102	832	623	322	213	0
1000	1000	17023	14042	11114	8024	6275	4978	4804	4736	4616	4351	4177	4099	3998	3896	3708	3148	2620	1199	636	391	189	128	0
1000	1500	20026	16859	13366	9481	7659	6918	6497	5831	5246	4610	4271	4057	3704	3655	3049	1601	1238	843	315	218	138	75	0
1000	2000	22495	18764	14921	10539	9084	7740	6830	6373	5480	4704	4407	3992	3596	3330	1957	1122	873	624	268	155	90	46	0
1000	2500	24717	20601	16332	11001	9794	8318	7090	6583	5633	4794	4338	3811	3566	2927	1197	1012	823	521	300	149	49	26	0

P	G	X																					
kPa	kg/m²/s	-0.50	-0.40	-0.30	-0.20	-0.15	-0.10	-0.05	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.60	0.70	0.80	0.90	1.0
1000	3000	26264	22053	17370	11532	10209	8496	7195	6673	5671	4871	4244	3718	3325	2007	977	895	701	583	313	168	59	24	0
1000	3500	27894	23473	18245	11516	10075	8480	7278	6704	5714	4887	4229	3597	3109	1924	1223	919	831	690	431	247	80	33	0
1000	4000	29406	24586	18990	11029	9419	8550	7359	6714	5752	4750	4075	3520	3031	2210	1620	1230	1090	890	545	300	101	40	0
1000	4500	30773	25743	19791	11226	9952	9143	7572	6924	5778	4571	3881	3430	2986	2349	1805	1456	1249	1030	629	331	122	51	0
1000	5000	31994	26863	20592	12193	10358	9185	7623	6934	5919	4492	3722	3317	2924	2357	1874	1562	1337	1109	703	372	146	64	0
1000	5500	33271	27872	21588	13122	10898	9280	7551	6744	6006	4590	3694	3272	2887	2358	1938	1664	1428	1200	781	427	173	78	0
1000	6000	34314	28814	22490	14247	11388	9491	7633	6655	6024	4616	3548	3236	2856	2372	2006	1746	1506	1280	856	477	204	95	0
1000	6500	35402	29678	23127	14949	11882	9883	7866	6765	6151	4649	3592	3194	2864	2403	2060	1829	1587	1362	935	530	236	112	0
1000	7000	36417	30478	23637	15247	12338	10051	8088	6875	6185	4676	3617	3231	2818	2445	2122	1909	1670	1445	1008	583	269	129	0
1000	7500	37289	31065	24195	16170	12803	10604	8228	6965	6238	4694	3628	3251	2897	2480	2219	1968	1736	1512	1074	630	291	140	0
1000	8000	38003	31712	25017	17157	13534	11049	8426	6995	6294	4822	3674	3301	2917	2547	2272	2021	1794	1573	1136	668	312	150	0
2000	0	7060	6243	5413	4622	4189	3713	3173	2594	2165	1704	1302	970	745	587	491	438	380	361	323	317	232	170	0
2000	50	7497	6756	6040	5351	4927	4460	3982	3450	3005	2552	2160	1834	1613	1447	1331	1209	1089	1069	924	845	658	373	0
2000	100	8767	7820	7040	6207	5946	5556	5241	4757	4071	3657	3326	3072	2933	2801	2599	2487	2393	2313	1996	1720	1123	594	0
2000	300	9784	8590	7775	7108	6722	6403	6064	5659	5220	4908	4646	4362	4026	3725	3563	3475	3375	3276	2998	2266	1252	690	0
2000	500	11464	9687	8430	7528	6977	6611	6260	6084	5540	5280	4924	4584	4373	4197	4076	3929	3828	3695	3362	1898	1109	609	0
2000	750	13730	11557	9579	7868	7076	6656	6388	6097	5696	5338	5083	4870	4700	4590	4478	4396	4033	3811	1948	1194	700	229	0
2000	1000	16027	13171	10583	7982	7118	6692	6371	6185	5781	5417	5197	5083	4992	4961	4792	4196	3311	2751	1260	597	359	174	0
2000	1500	18947	15537	12233	9416	8215	7670	7342	6660	6095	5463	5141	4871	4766	4524	4389	2926	1903	897	512	288	163	97	0
2000	2000	21106	17297	13588	10513	9584	8982	8305	7261	6199	5406	4996	4595	4283	3824	3026	1357	1172	682	418	196	97	60	0
2000	2500	23353	19098	14933	11161	10279	8996	8116	7196	5976	5302	4856	4552	3943	3328	1613	1237	958	556	313	157	53	29	0
2000	3000	25197	20509	15816	11602	10578	8792	7549	7112	5860	5169	4798	4483	3798	2570	1185	1020	731	594	331	172	59	27	0
2000	3500	26816	21723	16526	11317	10169	8672	7475	7057	5794	5042	4687	4310	3476	2403	1342	979	839	697	442	254	83	36	0
2000	4000	28328	22765	16902	10802	9806	8752	7542	7103	5878	4951	4485	3868	3301	2367	1642	1318	1147	996	606	318	104	40	0
2000	4500	29717	23920	17644	10857	9984	8899	7663	7149	5913	4875	4223	3760	3206	2375	1758	1445	1258	1062	653	340	119	47	0
2000	5000	30638	24767	18164	11811	10290	9037	7624	7195	5997	4789	4069	3605	3089	2389	1803	1545	1346	1131	712	380	134	56	0
2000	5500	32102	25866	18832	12769	10862	9069	7652	7041	6021	4783	3970	3532	3006	2379	1897	1647	1440	1212	781	412	153	67	0
2000	6000	33085	26751	19986	13576	11244	9316	7681	6987	6065	4800	3812	3481	2959	2391	1992	1742	1516	1287	848	452	177	80	0
2000	6500	34156	27592	20946	14138	11703	9812	7927	6933	6099	4851	3728	3431	2947	2452	2094	1842	1602	1371	928	499	205	95	0
2000	7000	35131	28383	21563	14625	12253	10016	8186	6988	6134	4932	3753	3344	2933	2513	2190	1935	1692	1458	1006	551	233	110	0
2000	7500	35897	29010	22130	15499	12704	10558	8396	7041	6198	5027	3844	3322	2983	2581	2286	2013	1767	1530	1073	599	247	118	0
2000	8000	36663	29609	22628	16442	13306	10940	8676	7070	6292	5167	3886	3403	3098	2696	2363	2077	1827	1595	1134	633	259	123	0
3000	0	6741	6001	5272	4593	4213	3873	3447	2943	2431	1979	1551	1181	929	741	615	539	482	443	396	350	247	178	0
3000	50	7222	6535	5910	5303	4961	4653	4297	3850	3325	2890	2482	2126	1884	1693	1549	1449	1361	1333	1219	1105	704	429	0
3000	100	8514	7599	6831	6315	6057	5809	5525	5121	4495	3921	3575	3415	3262	3171	3010	2948	2926	2771	2483	2059	1264	672	0
3000	300	9536	8324	7523	7171	7064	6874	6780	6474	6115	5666	5165	4849	4508	4218	3971	3752	3545	3485	3140	2620	1630	893	0
3000	500	10708	9149	8018	7426	7188	7073	6950	6649	6453	5959	5439	5061	4767	4432	4259	4150	3967	3742	3589	2645	1604	956	0

P	G	X																				
kPa	kg/m²/s	-0.50	-0.40	-0.30	-0.20	-0.15	-0.10	-0.05	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.60	0.70	0.80	0.90	1.0
3000	750	12850	10680	8910	7794	7444	7249	7010	6753	6553	6159	5644	5287	4988	4677	4591	4477	4271	3926	3069	1951	930	382	0
3000	1000	14637	12105	9835	7934	7668	7280	7085	6777	6547	6178	5762	5420	5207	4928	4690	4459	3879	3581	2405	1146	587	270	0
3000	1500	17032	14038	11355	9127	8517	8118	7806	7186	6517	6030	5546	5170	4998	4699	4281	3622	3030	2756	755	656	256	139	0
3000	2000	18967	15630	12632	10069	9300	8626	8094	7373	6337	5718	5192	4738	4342	3782	3448	2612	1739	938	499	279	115	82	0
3000	2500	21002	17244	13569	10901	9793	8745	7997	7221	6085	5432	4993	4483	3959	3547	2900	1819	978	657	342	169	63	39	0
3000	3000	22678	18551	14553	11208	10022	8672	7642	6860	5771	5187	4839	4355	3698	3152	2289	1188	774	578	348	179	63	32	0
3000	3500	24225	19619	15027	10936	9909	8471	7428	6681	5567	5023	4646	4230	3567	2745	1684	1107	859	717	458	268	92	39	0
3000	4000	25515	20591	15544	10471	9773	8428	7236	6508	5489	4877	4475	3897	3404	2484	1609	1338	1175	1004	625	334	110	41	0
3000	4500	26660	21487	15956	10512	9920	8426	7206	6588	5452	4690	4299	3747	3179	2366	1680	1410	1235	1079	668	355	119	47	0
3000	5000	27501	22290	16371	11621	10005	8768	7328	6596	5395	4583	4141	3624	3095	2314	1740	1498	1329	1142	717	382	131	54	0
3000	5500	28809	23183	17231	12402	10644	8980	7486	6632	5297	4509	3993	3593	3009	2318	1828	1606	1429	1215	781	400	147	63	0
3000	6000	29772	24039	18048	13154	11082	9224	7628	6695	5194	4444	3860	3543	2963	2333	1936	1719	1506	1282	839	434	168	75	0
3000	6500	30660	24751	18858	13660	11303	9721	7856	6714	5329	4555	3791	3514	2974	2439	2068	1835	1598	1364	917	479	194	89	0
3000	7000	31524	25478	19488	14216	11986	10000	8174	6762	5540	4605	3787	3398	2974	2535	2197	1944	1696	1457	999	531	223	104	0
3000	7500	32450	26191	20150	14817	12357	10509	8486	6885	5646	4685	3850	3328	3008	2644	2326	2034	1775	1531	1067	574	239	112	0
3000	8000	33419	26895	20708	15335	12944	10989	8752	6939	5798	4902	3882	3428	3160	2801	2418	2105	1838	1597	1129	605	253	119	0
4000	0	6381	5752	5128	4548	4242	3936	3584	3130	2568	2129	1697	1313	1050	850	711	621	554	502	410	364	254	180	0
4000	50	6880	6277	5741	5224	4956	4680	4373	3972	3417	2998	2595	2237	2000	1804	1652	1535	1442	1369	1311	1192	684	438	0
4000	100	8011	7253	6657	6198	6004	5816	5606	5247	4591	4041	3718	3507	3351	3236	3169	3116	3095	2962	2756	2332	1390	736	0
4000	300	9066	7896	7285	6976	6926	6915	6852	6577	6301	5647	5182	4899	4567	4381	4134	3843	3655	3534	3113	2592	1710	951	0
4000	500	9985	8504	7652	7150	7021	6982	6952	6774	6468	5916	5456	5074	4764	4526	4359	4094	3913	3788	3335	2600	1802	1063	0
4000	750	11731	9835	8338	7458	7240	7129	6997	6854	6548	6042	5608	5226	4885	4653	4503	4249	4031	3766	3124	2337	1312	499	0
4000	1000	13263	11165	9133	7771	7434	7226	7079	6895	6489	6073	5618	5217	4915	4655	4478	4060	3783	3395	2534	1603	660	342	0
4000	1500	15443	12792	10403	8532	8082	7792	7442	7030	6349	5917	5374	4931	4566	4185	3806	3452	2950	2641	984	643	337	192	0
4000	2000	17246	14234	11444	9118	8485	8116	7532	6839	6023	5518	4977	4460	4078	3687	3149	2588	2001	1136	597	346	160	120	0
4000	2500	19139	15660	12361	9638	8686	8097	7335	6559	5639	5046	4664	4199	3742	3222	2894	2018	997	699	397	180	85	47	0
4000	3000	20712	16899	13218	9948	8844	8066	7097	6258	5337	4714	4364	4009	3524	2980	2452	1355	792	551	386	185	70	37	0
4000	3500	22036	17946	13878	10050	8953	7952	6901	5838	5133	4604	4242	3868	3322	2682	1847	1161	902	724	503	289	98	40	0
4000	4000	23156	18859	14581	10021	9185	7989	6720	5582	4995	4394	3999	3601	3077	2372	1519	1304	1136	977	620	335	111	42	0
4000	4500	24287	19744	15016	10323	9466	8133	6747	5679	4908	4235	3835	3468	2961	2265	1556	1368	1201	1071	666	355	119	47	0
4000	5000	25296	20551	15551	11245	9805	8384	6855	5713	4900	4170	3725	3394	2871	2200	1609	1423	1294	1133	710	369	128	52	0
4000	5500	26166	21303	16222	12085	10392	8792	7044	5839	4839	4163	3690	3380	2867	2201	1732	1547	1401	1201	764	391	141	60	0
4000	6000	27009	21996	17079	12684	10801	9013	7480	6023	4827	4029	3633	3352	2830	2223	1865	1678	1483	1266	817	421	160	70	0
4000	6500	27791	22656	17646	13170	11092	9600	7788	6089	4919	3994	3618	3375	2884	2364	2030	1815	1579	1345	888	459	183	83	0
4000	7000	28558	23318	18225	13719	11824	9929	8079	6202	5003	3973	3650	3318	2928	2496	2173	1925	1674	1432	964	507	210	97	0
4000	7500	29348	23946	18769	14185	12235	10422	8409	6333	5108	4173	3686	3285	2995	2650	2327	2020	1753	1505	1031	539	225	105	0
4000	8000	30161	24554	19220	14557	12609	10986	8778	6604	5171	4388	3772	3408	3178	2822	2429	2096	1818	1572	1094	570	239	112	0

P	G	X																						
kPa	kg/m²/s	-0.50	-0.40	-0.30	-0.20	-0.15	-0.10	-0.05	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.60	0.70	0.80	0.90	1.0
5000	0	6044	5513	4986	4500	4239	3976	3666	3277	2677	2242	1808	1417	1154	944	795	694	619	561	456	366	257	191	0
5000	50	6547	6028	5573	5138	4921	4675	4407	4046	3467	3055	2662	2309	2065	1869	1715	1595	1493	1387	1330	1160	608	385	0
5000	100	7615	6922	6388	6040	5888	5703	5517	5192	4529	3997	3709	3524	3374	3240	3148	3053	3000	2837	2575	2202	1460	753	0
5000	300	8492	7453	6937	6709	6623	6510	6401	6207	5915	5395	4980	4709	4502	4302	3938	3662	3502	3255	2890	2511	1670	989	0
5000	500	9226	7886	7222	6839	6746	6655	6577	6460	6113	5594	5196	4866	4637	4339	4140	3882	3686	3517	3085	2490	1880	1104	0
5000	750	10677	9042	7794	7085	6908	6789	6666	6491	6126	5749	5213	4906	4675	4350	4160	3851	3574	3330	2760	2380	1519	814	0
5000	1000	12213	10204	8466	7447	7095	6989	6834	6568	6028	5726	5182	4796	4545	4194	3883	3496	3281	2974	2476	1683	690	379	0
5000	1500	14030	11668	9617	8115	7597	7296	7024	6470	5710	5375	4875	4438	4167	3795	3357	2941	2531	2290	914	592	393	200	0
5000	2000	15633	12936	10401	8530	7889	7408	6946	6107	5170	4836	4340	3913	3599	3257	2909	2412	1979	1182	638	354	188	130	0
5000	2500	17335	14268	11308	8887	7972	7432	6712	5661	4880	4445	4017	3662	3295	2876	2689	1915	955	651	447	195	99	51	0
5000	3000	18794	15433	12150	9231	8180	7463	6490	5427	4718	4265	3857	3476	3104	2578	2283	1429	708	533	405	179	73	41	0
5000	3500	19936	16374	12894	9768	8306	7477	6368	5026	4484	3984	3644	3312	2932	2394	1781	1164	910	706	513	290	103	42	0
5000	4000	20949	17217	13569	9991	8683	7658	6295	4783	4200	3584	3367	3140	2745	2274	1402	1188	1060	922	593	320	111	44	0
5000	4500	21962	18016	14114	10137	9063	7837	6323	4905	4130	3522	3305	3023	2672	2065	1424	1245	1128	1046	649	346	117	46	0
5000	5000	22867	18766	14525	10880	9540	8183	6486	5030	4103	3487	3287	3017	2684	2024	1455	1329	1224	1112	695	362	124	51	0
5000	5500	23661	19456	15309	11569	10048	8548	6741	5245	4051	3480	3299	3060	2672	2047	1628	1480	1351	1176	743	379	135	57	0
5000	6000	24391	20103	15958	12239	10650	8921	7328	5430	4008	3507	3314	3079	2696	2057	1747	1598	1449	1240	793	405	152	67	0
5000	6500	25098	20718	16511	12734	10892	9511	7643	5637	4183	3523	3357	3128	2771	2258	1947	1783	1549	1314	855	437	172	78	0
5000	7000	25860	21312	16907	13189	11608	9908	7949	5781	4373	3553	3386	3182	2857	2430	2136	1893	1639	1396	926	482	197	91	0
5000	7500	26597	21982	17360	13563	11914	10298	8281	6006	4572	3786	3444	3201	2944	2603	2250	1988	1716	1466	990	512	211	98	0
5000	8000	27254	22428	17865	13912	12316	10851	8676	6217	4805	4010	3629	3362	3178	2817	2409	2068	1783	1533	1052	543	225	105	0
6000	0	5731	5279	4832	4421	4202	3971	3699	3320	2709	2275	1852	1467	1212	1000	849	741	659	596	481	376	264	200	0
6000	50	6221	5778	5386	5013	4826	4615	4377	4045	3453	3101	2662	2323	2082	1888	1734	1607	1496	1375	1217	1050	552	365	0
6000	100	7293	6608	6137	5827	5692	5484	5325	5057	4421	3908	3637	3438	3293	3158	3051	2951	2822	2667	2380	1959	1340	781	0
6000	300	7916	7059	6594	6321	6184	6080	6005	5815	5487	5127	4756	4510	4179	3899	3689	3469	3220	2976	2681	2238	1534	934	0
6000	500	8442	7361	6837	6459	6371	6294	6232	5979	5738	5247	4857	4575	4384	4140	3924	3700	3396	3133	2825	2306	1695	989	0
6000	750	9850	8407	7368	6692	6497	6383	6290	6148	5765	5330	4896	4544	4345	4058	3836	3594	3287	2988	2492	2150	1513	829	0
6000	1000	11155	9448	7890	7011	6705	6596	6513	6201	5722	5293	4782	4395	4200	3863	3597	3239	2971	2582	2271	1071	697	391	0
6000	1500	12900	10809	8946	7670	7247	7095	6838	6155	5374	4993	4480	4054	3681	3310	2945	2651	2420	2058	802	454	366	203	0
6000	2000	14384	12021	9843	7924	7491	7137	6719	5820	4825	4486	3913	3505	3138	2830	2660	2227	1743	998	590	308	195	133	0
6000	2500	15946	13238	10588	8198	7537	7137	6356	5453	4594	4053	3513	3143	2793	2436	2303	1757	882	600	410	190	104	56	0
6000	3000	17244	14290	11366	8747	7807	7179	6230	5236	4310	3714	3223	2910	2595	2303	2015	1283	580	484	362	173	75	42	0
6000	3500	18285	15146	12121	9342	8074	7311	6104	4836	4012	3411	3065	2723	2439	2053	1629	991	766	595	479	257	100	44	0
6000	4000	19244	15944	12744	9717	8398	7461	6052	4528	3778	3034	2864	2605	2356	1933	1363	1082	948	821	534	300	107	45	0
6000	4500	20189	16677	13217	9932	8608	7473	5996	4479	3698	2919	2760	2510	2308	1865	1344	1144	1030	941	580	312	111	46	0
6000	5000	21078	17381	13717	10406	9037	7777	6048	4720	3742	2979	2786	2506	2302	1820	1405	1243	1128	1023	618	321	115	49	0
6000	5500	21815	18023	14305	11029	9565	8133	6431	4925	3760	3104	2820	2613	2375	1884	1519	1391	1242	1088	667	340	125	54	0

P	G	X																					
kPa	kg/m²/s	-0.50	-0.40	-0.30	-0.20	-0.15	-0.10	-0.05	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.60	0.70	0.80	0.90	1.0
6000	6000	22445	18634	14956	11804	10258	8850	6962	5081	3795	3178	2897	2716	2419	1923	1641	1533	1353	1154	719	366	141	63	0
6000	6500	23077	19207	15518	12290	10703	9429	7447	5256	3880	3221	2977	2810	2500	2134	1864	1691	1451	1221	780	398	160	73	0
6000	7000	23777	19755	15984	12669	11390	9828	7703	5445	4019	3275	3071	2896	2618	2314	2051	1796	1534	1294	847	440	182	85	0
6000	7500	24445	20282	16410	13004	11680	10081	8027	5661	4210	3413	3162	2991	2773	2505	2171	1895	1614	1367	913	471	195	91	0
6000	8000	25032	20784	16796	13464	11986	10638	8425	5800	4408	3658	3437	3221	3099	2754	2366	1986	1692	1442	978	502	208	97	0
7000	0	5445	5059	4676	4323	4139	3937	3677	3322	2696	2256	1848	1479	1243	1036	891	778	692	621	525	389	267	209	0
7000	50	5919	5536	5191	4863	4698	4520	4306	3998	3399	2986	2624	2264	2042	1859	1712	1588	1477	1366	1151	1010	473	325	0
7000	100	6912	6301	5871	5584	5462	5261	5095	4849	4271	3776	3499	3290	3142	3034	2906	2850	2651	2486	2123	1673	1205	768	0
7000	300	7445	6709	6259	6020	5914	5761	5662	5495	5182	4752	4464	4070	3764	3611	3417	3250	3028	2738	2286	1994	1408	869	0
7000	500	7842	6895	6435	6188	5996	5931	5818	5672	5408	4922	4521	4196	3989	3812	3602	3459	3221	2905	2482	1985	1547	869	0
7000	750	9129	7841	6867	6263	6154	5998	5895	5776	5430	4987	4538	4131	3918	3709	3464	3327	3118	2770	2312	1904	1400	742	0
7000	1000	10186	8774	7390	6532	6313	6276	6162	5864	5366	4920	4399	3935	3723	3447	3112	2884	2713	2432	2085	767	506	341	0
7000	1500	11920	10072	8460	7262	6915	6647	6308	5729	5059	4561	4039	3612	3279	2991	2698	2490	2264	1591	599	372	318	191	0
7000	2000	13294	11209	9172	7557	7279	6769	6187	5327	4570	4020	3552	3174	2864	2566	2353	1919	1406	793	483	267	197	134	0
7000	2500	14680	12245	9774	7920	7382	6765	5895	4977	4178	3639	3207	2867	2552	2211	1941	1487	813	521	342	177	103	58	0
7000	3000	15871	13214	10463	8259	7522	6778	5785	4761	3971	3366	3014	2640	2333	2111	1685	951	493	429	307	157	77	43	0
7000	3500	16889	14072	11223	8783	7744	6972	5738	4518	3739	3127	2816	2482	2188	1798	1357	851	631	531	388	224	96	44	0
7000	4000	17783	14824	11868	9277	8077	7118	5593	4226	3539	2855	2616	2362	2104	1710	1251	957	789	681	444	255	99	44	0
7000	4500	18619	15498	12439	9619	8281	7208	5381	4156	3422	2650	2472	2268	2057	1647	1239	1006	867	779	487	266	102	45	0
7000	5000	19434	16132	12870	10084	8686	7415	5486	4350	3409	2611	2486	2251	2040	1619	1279	1052	950	854	526	277	106	47	0
7000	5500	20138	16733	13579	10563	9272	7844	6153	4649	3405	2688	2460	2325	2076	1662	1397	1217	1065	933	576	298	115	52	0
7000	6000	20703	17309	14047	11354	9947	8657	6697	4756	3417	2725	2487	2353	2087	1697	1476	1339	1184	1018	637	327	131	60	0
7000	6500	21284	17855	14610	11951	10355	9156	7135	4905	3437	2733	2525	2442	2241	1938	1688	1515	1303	1103	702	360	149	69	0
7000	7000	21889	18357	15013	12260	10817	9456	7309	4949	3504	2872	2648	2499	2348	2094	1852	1615	1393	1182	771	401	170	80	0
7000	7500	22505	18841	15385	12539	11244	9779	7455	5004	3629	3017	2792	2596	2488	2263	2039	1776	1504	1264	838	433	182	86	0
7000	8000	23064	19305	15794	12917	11519	10059	7792	5163	3777	3222	3120	3063	2927	2605	2282	1893	1592	1345	904	463	193	91	0
8000	0	5168	4836	4507	4201	4041	3854	3613	3270	2628	2169	1782	1440	1237	1045	902	794	713	651	553	403	268	218	0
8000	50	5624	5292	4985	4692	4543	4372	4149	3832	3192	2834	2496	2163	1951	1795	1666	1555	1454	1357	1117	935	425	289	0
8000	100	6526	5943	5604	5334	5217	5068	4856	4621	4092	3642	3337	3121	2981	2862	2758	2646	2417	2240	1679	1430	997	630	0
8000	300	7008	6328	5931	5683	5610	5428	5341	5148	4849	4429	4023	3700	3456	3273	3104	2915	2738	2440	2061	1765	1291	799	0
8000	500	7275	6563	6006	5735	5670	5527	5479	5320	5061	4637	4253	3848	3596	3386	3212	3062	2903	2540	2051	1702	1203	727	0
8000	750	8422	7294	6436	5888	5779	5598	5534	5400	5102	4721	4266	3790	3509	3260	3082	2926	2726	2440	1832	1472	743	437	0
8000	1000	9557	8109	6846	6104	5946	5879	5716	5467	5056	4662	4125	3629	3344	3021	2823	2573	2308	2156	1695	558	360	257	0
8000	1500	10928	9303	7945	6700	6471	6191	5834	5346	4761	4281	3737	3270	2903	2576	2328	2089	1653	847	504	284	236	174	0
8000	2000	12236	10357	8597	7082	6720	6312	5727	4995	4288	3739	3224	2816	2497	2162	1937	1644	1019	615	401	226	177	124	0
8000	2500	13416	11224	9098	7492	6792	6328	5554	4688	3976	3248	2831	2473	2161	1816	1482	1033	644	449	300	160	98	56	0
8000	3000	14520	12118	9659	7662	6986	6332	5471	4484	3690	3013	2539	2236	1966	1741	1308	801	447	374	272	140	75	42	0

P	G	X																						
kPa	kg/m²/s	-0.50	-0.40	-0.30	-0.20	-0.15	-0.10	-0.05	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.60	0.70	0.80	0.90	1.0
8000	3500	15484	12983	10368	8187	7425	6655	5404	4332	3524	2841	2384	2084	1824	1509	1109	705	530	473	329	185	88	42	0
8000	4000	16311	13667	10980	8720	7719	6847	5344	4104	3286	2569	2235	1991	1769	1466	996	792	652	564	369	211	90	42	0
8000	4500	17066	14296	11589	9247	7920	6993	5285	3901	3057	2400	2103	1968	1787	1481	1156	867	736	622	416	226	93	43	0
8000	5000	17776	14881	12049	9652	8300	7157	5284	4028	3031	2364	2106	1968	1796	1492	1229	926	817	732	465	241	97	45	0
8000	5500	18408	15439	12558	10192	8838	7674	5811	4358	2967	2344	2184	2033	1897	1564	1365	1110	967	825	519	266	107	49	0
8000	6000	18958	15967	13123	10912	9487	8362	6240	4571	3022	2436	2246	2114	1931	1625	1404	1237	1101	927	585	297	122	56	0
8000	6500	19522	16465	13576	11430	10064	8727	6580	4580	3030	2466	2336	2218	2103	1824	1600	1435	1219	1023	653	334	140	66	0
8000	7000	20052	16929	14000	11762	10440	8971	6909	4597	3157	2529	2456	2302	2227	1984	1759	1543	1309	1103	720	374	160	76	0
8000	7500	20630	17393	14378	11934	10674	9193	6993	4670	3235	2614	2500	2402	2361	2155	1912	1662	1407	1185	785	406	172	81	0
8000	8000	21184	17841	14750	12269	10862	9590	7195	4890	3522	3100	3020	2900	2750	2520	2181	1792	1503	1266	849	436	183	86	0
9000	0	4897	4610	4324	4058	3918	3751	3530	3203	2561	2086	1717	1400	1223	1043	908	803	724	665	575	410	260	218	0
9000	50	5333	5043	4768	4504	4370	4215	4010	3714	3083	2620	2304	2053	1888	1738	1617	1512	1436	1302	1074	870	397	286	0
9000	100	6188	5656	5348	5075	4959	4755	4610	4384	3903	3426	3137	2949	2830	2682	2576	2323	2061	1845	1438	1170	787	540	0
9000	300	6656	6076	5637	5361	5202	5082	4997	4830	4499	4013	3621	3292	3103	2905	2797	2589	2405	2200	1829	1408	1100	699	0
9000	500	6923	6232	5761	5487	5286	5166	5082	4930	4678	4213	3770	3393	3211	2971	2869	2612	2385	2090	1740	1413	1002	591	0
9000	750	7891	6892	6108	5569	5379	5183	5079	4867	4629	4212	3680	3294	3068	2841	2690	2429	2104	1809	1452	1026	452	307	0
9000	1000	8856	7633	6507	5790	5504	5304	5135	4821	4517	4158	3610	3186	2897	2588	2367	2099	1850	1647	1282	292	184	160	0
9000	1500	10300	8807	7538	6447	6026	5550	5193	4672	4243	3800	3317	2855	2514	2151	1963	1616	1224	596	354	179	144	114	0
9000	2000	11475	9729	8165	6827	6194	5689	5143	4416	3789	3354	2789	2385	2088	1799	1494	1017	497	377	214	128	101	82	0
9000	2500	12645	10690	8710	7139	6455	5901	5130	4240	3537	2919	2480	2097	1797	1487	1135	682	427	335	203	125	78	47	0
9000	3000	13639	11492	9277	7430	6715	5992	5076	4097	3311	2657	2213	1893	1642	1376	934	598	390	293	196	116	60	37	0
9000	3500	14478	12211	9916	8021	7090	6248	5023	4040	3222	2514	2067	1802	1572	1308	914	603	462	407	275	149	79	40	0
9000	4000	15253	12857	10490	8427	7431	6476	5009	3987	3040	2304	1974	1757	1559	1325	938	743	585	511	326	173	83	40	0
9000	4500	15951	13449	11000	8924	7725	6727	5000	3869	3004	2194	1929	1714	1587	1376	1088	827	675	556	366	192	86	41	0
9000	5000	16595	13997	11466	9312	8078	7074	5022	3965	2943	2142	1957	1791	1619	1433	1158	898	753	636	425	215	91	43	0
9000	5500	17199	14521	11926	9804	8617	7517	5689	4188	2963	2172	2002	1902	1701	1507	1311	1008	897	752	484	244	100	47	0
9000	6000	17728	15017	12440	10414	9131	7919	5988	4325	2977	2266	2078	1965	1767	1567	1369	1135	1023	871	552	278	115	54	0
9000	6500	18263	15485	12858	10901	9555	8318	6284	4421	3006	2364	2201	2102	1910	1737	1550	1354	1150	968	619	317	133	63	0
9000	7000	18768	15923	13245	11180	9790	8553	6433	4465	3101	2412	2305	2175	2133	1905	1661	1445	1232	1047	684	356	153	72	0
9000	7500	19275	16337	13594	11339	9994	8751	6460	4540	3180	2450	2400	2300	2270	2050	1799	1544	1318	1126	746	387	164	78	0
9000	8000	19759	16735	13931	11631	10222	9031	6581	4784	3566	3071	2984	2835	2705	2445	2056	1711	1435	1207	808	416	175	82	0
10000	0	4624	4375	4128	3896	3774	3627	3426	3122	2501	2018	1664	1365	1208	1041	910	809	734	677	582	404	244	205	0
10000	50	5040	4787	4542	4302	4182	4042	3857	3586	2977	2514	2217	1984	1824	1678	1583	1501	1402	1250	1018	758	386	281	0
10000	100	5711	5424	5083	4812	4696	4507	4371	4158	3699	3259	2970	2830	2654	2505	2354	2059	1840	1620	1293	999	668	467	0
10000	300	6240	5751	5329	5036	4934	4777	4690	4523	4197	3777	3361	3136	2994	2803	2635	2398	2250	1922	1707	1267	915	505	0
10000	500	6422	5774	5441	5059	4945	4837	4744	4583	4328	3920	3461	3206	3005	2804	2640	2386	2147	1830	1528	1203	806	431	0
10000	750	7259	6426	5740	5233	5035	4842	4761	4501	4263	3879	3404	3093	2879	2640	2443	2071	1760	1455	1080	713	347	238	0

P	G	X																				
kPa	kg/m²/s	-0.50	-0.40	-0.30	-0.20	-0.15	-0.10	-0.05	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.60	0.70	0.80	0.90	1.0
10000	1000	8156	7090	6125	5478	5179	4985	4762	4439	4149	3793	3295	2886	2595	2280	1986	1783	1465	1183	356	156	108	105	0
10000	1500	9449	8185	7053	6227	5689	5217	4781	4311	3892	3446	2977	2526	2095	1865	1547	1203	378	295	176	79	59	51	0
10000	2000	10490	8949	7655	6479	5965	5398	4762	4131	3467	2960	2452	2020	1708	1391	1054	393	247	183	125	65	50	46	0
10000	2500	11536	9833	8292	6889	6216	5619	4784	4013	3282	2691	2188	1776	1469	1177	738	342	288	182	140	80	54	39	0
10000	3000	12449	10561	8790	7196	6491	5789	4822	3893	3116	2432	1939	1580	1354	998	675	396	337	232	176	98	50	32	0
10000	3500	13181	11191	9261	7712	6887	6007	4842	3862	2998	2277	1809	1526	1314	1076	775	528	406	365	254	131	75	38	0
10000	4000	13882	11788	9761	8080	7079	6163	4875	3813	2936	2079	1704	1521	1251	1153	881	694	525	445	299	153	76	39	0
10000	4500	14555	12363	10227	8450	7344	6374	4885	3798	2877	2027	1709	1562	1331	1279	1048	763	611	513	342	174	81	40	0
10000	5000	15087	12776	10637	8882	7723	6804	4955	3928	2889	2082	1715	1608	1460	1314	1073	832	683	575	395	200	87	42	0
10000	5500	15617	13257	11054	9422	8279	7203	5517	4119	2942	2106	1824	1763	1638	1478	1261	964	822	681	453	231	96	45	0
10000	6000	16191	13799	11553	9797	8723	7611	5821	4226	3014	2189	1975	1867	1723	1539	1323	1109	963	816	526	267	111	52	0
10000	6500	16692	14162	11890	10082	9097	7925	5990	4326	3023	2297	2073	2020	1843	1697	1500	1314	1098	923	595	305	129	60	0
10000	7000	17149	14598	12284	10292	9215	8047	6128	4397	3082	2339	2209	2103	2006	1850	1618	1394	1179	1004	658	343	147	70	0
10000	7500	17628	15027	12656	10529	9450	8245	6145	4440	3190	2370	2320	2190	2170	2000	1740	1491	1270	1084	719	373	159	75	0
10000	8000	18123	15428	12988	10706	9587	8466	6263	4626	3587	3056	2981	2800	2700	2347	2006	1665	1403	1174	781	402	170	80	0
11000	0	4348	4133	3918	3717	3611	3484	3303	3026	2449	1975	1634	1349	1191	1034	910	812	741	688	586	399	232	169	0
11000	50	4741	4521	4306	4089	3980	3854	3687	3441	2883	2439	2149	1922	1761	1617	1541	1421	1298	1156	935	709	383	272	0
11000	100	5463	5064	4814	4548	4432	4244	4110	3916	3502	3081	2849	2649	2501	2316	2153	1797	1593	1405	1113	869	555	373	0
11000	300	5858	5426	5036	4724	4611	4455	4181	4103	3921	3507	3167	2951	2759	2553	2320	2186	2020	1783	1400	990	639	402	0
11000	500	5992	5486	5086	4814	4627	4486	4224	4152	4011	3604	3236	3004	2786	2572	2367	2167	1903	1720	1280	943	587	299	0
11000	750	6744	6018	5382	4880	4672	4444	4240	4149	3883	3487	3099	2833	2577	2317	2090	1673	1341	1165	853	501	265	158	0
11000	1000	7566	6662	5735	5056	4796	4481	4296	4092	3690	3296	2892	2598	2270	2072	1734	1360	1014	700	210	125	93	83	0
11000	1500	8820	7620	6566	5582	5181	4710	4305	3990	3480	2990	2509	2150	1767	1417	1150	704	349	232	122	60	54	43	0
11000	2000	9679	8307	7114	5938	5486	4892	4334	3903	3179	2620	2105	1709	1417	1150	695	230	151	100	78	50	40	40	0
11000	2500	10658	9139	7791	6391	5806	5204	4381	3850	3085	2411	1849	1489	1233	910	390	230	187	139	113	66	47	32	0
11000	3000	11500	9847	8268	6855	6183	5436	4405	3763	2958	2206	1634	1351	1152	833	412	310	284	205	156	83	47	28	0
11000	3500	12131	10351	8680	7194	6472	5619	4429	3704	2904	2100	1508	1299	1116	921	552	426	358	311	239	114	69	36	0
11000	4000	12779	10902	9163	7496	6660	5806	4503	3671	2810	1932	1502	1340	1188	1033	763	614	469	388	269	138	72	37	0
11000	4500	13415	11397	9511	7891	6869	6015	4564	3675	2799	1905	1592	1434	1246	1141	926	729	571	442	312	161	77	39	0
11000	5000	13843	11786	9896	8194	7322	6430	4808	3828	2856	1958	1645	1491	1373	1255	993	780	610	493	359	188	84	41	0
11000	5500	14320	12195	10293	8722	7802	6799	5105	4029	2919	2064	1790	1651	1565	1403	1172	929	732	593	418	220	93	44	0
11000	6000	14952	12812	10646	9087	8110	7055	5299	4133	3030	2153	1951	1787	1673	1505	1297	1083	893	745	501	258	108	50	0
11000	6500	15435	13041	11056	9281	8423	7262	5384	4220	3063	2247	2028	1909	1794	1652	1465	1257	1051	873	574	297	125	58	0
11000	7000	15841	13511	11486	9607	8652	7494	5407	4290	3160	2356	2156	2035	1942	1777	1564	1373	1149	966	637	334	143	68	0
11000	7500	16264	13944	11897	9939	8715	7654	5459	4350	3240	2430	2300	2160	2115	1978	1702	1461	1250	1056	698	363	155	73	0
11000	8000	16754	14351	12202	10002	8817	7816	5608	4441	3512	2991	2912	2705	2606	2251	1990	1632	1388	1159	762	392	165	78	0
12000	0	4070	3883	3698	3525	3433	3322	3163	2914	2391	1936	1606	1334	1173	1026	909	814	745	694	588	397	225	141	0

P	G	X																				
kPa	kg/m²/s	-0.50	-0.40	-0.30	-0.20	-0.15	-0.10	-0.05	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.60	0.70	0.80	0.90	1.0
12000	50	4436	4247	4061	3869	3770	3658	3506	3285	2784	2367	2081	1857	1694	1565	1498	1357	1200	1087	867	667	381	242	0
12000	100	5023	4806	4538	4290	4171	3983	3844	3645	3267	2878	2711	2500	2257	2069	1905	1622	1460	1290	977	772	446	301	0
12000	300	5366	5081	4741	4434	4269	4138	3950	3838	3516	3199	2912	2701	2467	2285	2108	1940	1830	1630	1250	840	500	316	0
12000	500	5647	5188	4869	4445	4298	4131	3988	3819	3555	3240	2951	2724	2500	2310	2160	1875	1678	1474	1011	423	296	205	0
12000	750	6233	5596	5072	4528	4310	4067	3904	3659	3418	3067	2773	2526	2277	2039	1798	1396	1180	989	312	251	211	131	0
12000	1000	7031	6267	5500	4700	4430	4100	3855	3447	3243	2878	2516	2291	1905	1640	1420	1073	920	310	214	118	78	76	0
12000	1500	8214	7105	6221	5242	4662	4271	3813	3405	2952	2526	2112	1723	1389	1096	918	377	315	205	105	41	39	36	0
12000	2000	8959	7711	6598	5472	4982	4417	3841	3375	2830	2300	1816	1410	1109	911	385	119	110	77	71	50	37	31	0
12000	2500	9851	8471	7225	5977	5407	4720	3900	3367	2739	2119	1603	1215	971	753	293	172	139	119	99	59	40	27	0
12000	3000	10436	9128	7655	6409	5706	4923	3949	3364	2690	1985	1492	1101	889	689	354	300	245	195	154	81	45	26	0
12000	3500	11000	9572	7966	6675	5958	5076	4002	3360	2680	1910	1409	1138	922	772	414	404	329	294	221	109	66	35	0
12000	4000	11291	9879	8449	7028	6239	5226	4061	3326	2680	1904	1456	1244	1077	923	693	586	454	361	251	131	70	36	0
12000	4500	11695	10442	8797	7329	6398	5397	4163	3353	2698	1927	1529	1383	1174	1097	862	685	539	418	294	154	75	38	0
12000	5000	12117	10856	9117	7579	6726	5903	4418	3478	2772	2010	1637	1431	1254	1154	921	726	573	465	341	183	82	40	0
12000	5500	12466	11071	9431	7831	7005	6089	4517	3728	2908	2140	1867	1621	1469	1345	1105	909	704	564	401	214	91	43	0
12000	6000	13176	11559	9782	8050	7166	6225	4603	3885	3060	2229	1986	1781	1627	1472	1254	1065	868	721	483	252	105	49	0
12000	6500	14034	12051	10061	8249	7390	6426	4668	3941	3128	2355	2150	1949	1811	1623	1447	1220	1023	852	558	290	122	57	0
12000	7000	14607	12508	10487	8532	7609	6605	4731	4011	3192	2432	2217	2093	1955	1730	1554	1342	1126	945	622	326	140	66	0
12000	7500	14975	12908	10907	8703	7863	6710	4821	4080	3250	2490	2284	2170	2077	1921	1676	1441	1227	1034	683	355	152	72	0
12000	8000	15432	13298	11407	8898	8033	6904	4932	4219	3398	2827	2737	2527	2420	2168	1912	1606	1370	1142	749	384	162	76	0
13000	0	3793	3635	3479	3330	3252	3156	3018	2797	2329	1899	1580	1319	1154	1013	901	809	743	696	588	397	213	124	0
13000	50	4130	3972	3820	3656	3568	3468	3331	3130	2681	2290	2007	1794	1608	1446	1397	1209	1100	1022	830	621	349	209	0
13000	100	4638	4403	4194	3957	3853	3733	3587	3406	3117	2756	2491	2158	1965	1780	1626	1429	1283	1155	893	680	381	237	0
13000	300	4926	4647	4392	4097	3973	3831	3682	3514	3249	2900	2601	2301	2134	1917	1780	1610	1506	1350	996	709	408	249	0
13000	500	5166	4815	4483	4121	3960	3786	3626	3475	3234	2890	2591	2273	2008	1789	1581	1458	1353	1183	729	351	242	170	0
13000	750	5697	5178	4738	4148	3987	3736	3426	3292	2983	2690	2364	2094	1814	1561	1325	1056	980	718	272	157	91	87	0
13000	1000	6609	5850	5090	4267	4022	3704	3257	2793	2480	2240	1950	1650	1400	1188	975	820	700	280	216	110	70	56	0
13000	1500	7646	6687	5592	4656	4128	3775	3180	2723	2381	2003	1722	1383	1120	806	576	298	211	188	109	47	42	33	0
13000	2000	8210	7123	5974	4898	4389	3976	3224	2855	2358	1941	1564	1201	957	608	409	147	119	103	91	51	38	28	0
13000	2500	8606	7756	6470	5323	4771	4206	3326	2937	2349	1911	1447	1032	853	573	294	190	132	118	95	60	39	26	0
13000	3000	9035	8256	6921	5741	5059	4415	3380	3006	2397	1876	1400	1004	846	605	351	280	218	189	142	79	43	30	0
13000	3500	9331	8400	7115	5939	5262	4612	3512	3105	2505	1902	1409	1100	900	712	425	411	338	283	205	109	63	34	0
13000	4000	9691	8661	7357	6130	5481	4808	3669	3155	2576	1963	1514	1201	1002	885	696	577	448	359	246	127	67	35	0
13000	4500	10084	8806	7528	6429	5737	5021	3903	3235	2606	1994	1606	1331	1142	1025	825	683	532	408	287	150	72	36	0
13000	5000	10196	9011	7694	6642	6109	5250	4054	3302	2700	2059	1667	1425	1211	1098	893	738	570	453	331	177	79	38	0
13000	5500	10515	9388	8008	6796	6245	5407	4108	3467	2908	2326	1927	1633	1447	1315	1093	906	708	554	389	208	89	42	0
13000	6000	11438	10045	8263	7049	6418	5504	4148	3560	3084	2445	2078	1837	1638	1450	1247	1060	868	706	472	246	103	48	0

P	G	X																					
kPa	kg/m²/s	-0.50	-0.40	-0.30	-0.20	-0.15	-0.10	-0.05	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.60	0.70	0.80	0.90	1.0
13000	6500	12282	10449	8539	7274	6599	5602	4195	3624	3159	2496	2206	2103	1850	1619	1441	1225	1018	837	546	284	120	56	0
13000	7000	13064	11124	8837	7417	6726	5660	4210	3686	3218	2525	2260	2184	1998	1729	1549	1332	1120	931	610	321	138	65	0
13000	7500	13697	11712	9419	7523	6782	5711	4230	3716	3260	2540	2310	2240	2100	1870	1659	1435	1219	1021	673	350	149	71	0
13000	8000	14156	12071	9815	7586	6826	5818	4489	3964	3298	2722	2571	2415	2278	2102	1854	1589	1358	1132	739	379	160	75	0
14000	0	3505	3372	3240	3113	3046	2965	2846	2654	2242	1848	1544	1296	1129	992	884	799	736	691	585	384	202	113	0
14000	50	3808	3676	3552	3413	3338	3250	3129	2951	2557	2195	1919	1710	1527	1363	1230	1114	1035	930	790	565	310	185	0
14000	100	4244	4060	3897	3721	3617	3500	3371	3206	2909	2586	2280	1961	1791	1575	1469	1262	1193	1023	811	595	342	204	0
14000	300	4479	4268	4074	3858	3727	3586	3448	3301	2996	2701	2358	2100	1970	1756	1651	1481	1308	1143	842	615	347	217	0
14000	500	4680	4404	4184	3876	3713	3545	3401	3249	3001	2641	2373	2089	1825	1559	1422	1273	1087	1017	319	298	192	119	0
14000	750	5155	4929	4487	3917	3666	3417	3241	3056	2841	2505	2177	1849	1591	1332	1131	885	769	502	265	135	79	77	0
14000	1000	6001	5588	4980	4089	3670	3378	3049	2693	2399	2051	1731	1466	1244	1017	854	745	649	295	224	102	67	49	0
14000	1500	6787	6145	5185	4364	3798	3406	3003	2583	2218	1807	1498	1200	971	765	555	196	180	138	119	53	43	34	0
14000	2000	7188	6465	5394	4496	3995	3628	3201	2686	2221	1751	1444	1121	879	603	419	176	125	108	93	58	41	26	0
14000	2500	7630	6781	5886	4902	4465	4006	3295	2832	2224	1773	1391	1024	831	564	312	213	139	119	102	62	42	27	0
14000	3000	7824	7031	6139	5394	4701	4236	3320	2894	2333	1831	1396	1082	865	604	318	275	237	201	146	80	47	31	0
14000	3500	8111	7338	6268	5532	4884	4356	3417	2963	2433	1897	1444	1140	927	710	491	420	340	281	200	108	61	32	0
14000	4000	8329	7457	6488	5706	5185	4498	3518	2992	2511	2029	1603	1307	1103	854	722	590	467	365	245	125	65	33	0
14000	4500	8718	7543	6537	5730	5344	4748	3789	3092	2558	2105	1709	1449	1207	1005	835	676	558	421	287	148	70	34	0
14000	5000	8978	7649	6594	5732	5451	4912	3963	3214	2692	2161	1745	1510	1280	1062	916	746	599	465	329	174	76	36	0
14000	5500	9249	7760	6609	5753	5505	4944	4043	3419	3026	2433	1989	1746	1475	1298	1107	940	746	572	390	206	87	40	0
14000	6000	9831	8166	6738	5864	5509	4956	4110	3463	3170	2575	2209	1986	1686	1420	1253	1082	893	709	468	242	101	47	0
14000	6500	10687	8715	6808	5894	5553	4972	4129	3544	3208	2617	2326	2201	1908	1609	1448	1241	1034	834	539	280	118	55	0
14000	7000	11414	9448	7169	6008	5694	4993	4140	3605	3202	2682	2339	2261	2018	1745	1556	1343	1129	924	603	317	136	64	0
14000	7500	12199	10064	7714	6137	5700	5016	4159	3729	3240	2689	2350	2270	2120	1836	1638	1433	1216	1013	666	347	148	70	0
14000	8000	12874	10581	8108	6231	5878	5214	4370	3809	3276	2806	2508	2342	2217	2033	1803	1565	1338	1116	733	376	159	75	0
15000	0	3199	3087	2977	2871	2814	2746	2646	2481	2127	1772	1490	1258	1091	958	855	776	717	681	577	369	188	106	0
15000	50	3466	3358	3256	3140	3077	3012	2910	2744	2418	2086	1828	1557	1397	1232	1091	984	945	840	710	496	253	155	0
15000	100	3868	3711	3574	3417	3330	3208	3086	2879	2589	2323	2080	1783	1590	1430	1294	1158	1046	908	705	498	274	174	0
15000	300	4084	3904	3740	3529	3418	3247	3099	2924	2658	2379	2094	1864	1712	1578	1392	1238	1100	940	684	493	279	186	0
15000	500	4264	4017	3798	3541	3396	3201	3039	2886	2641	2341	2047	1816	1580	1395	1148	1044	896	652	408	346	148	95	0
15000	750	4699	4411	4119	3652	3388	3087	2889	2673	2403	2191	1895	1483	1262	1093	882	741	627	449	255	120	88	73	0
15000	1000	5650	5293	4743	3862	3420	2975	2691	2350	2063	1797	1493	1145	1030	881	721	536	447	320	237	94	61	48	0
15000	1500	6443	5572	4956	3998	3489	3025	2553	2232	1924	1620	1347	1053	908	705	549	287	223	128	123	58	45	36	0
15000	2000	6987	5872	5092	4181	3709	3176	2787	2330	1943	1687	1307	1016	873	664	447	218	176	120	102	64	46	30	0
15000	2500	7189	6313	5540	4723	4265	3665	3084	2535	2102	1759	1358	1067	889	627	378	259	176	143	111	77	49	28	0
15000	3000	7479	6642	5945	5136	4551	3906	3207	2635	2205	1837	1419	1137	925	670	464	380	290	234	171	96	56	31	0
15000	3500	7678	6918	6149	5310	4767	4162	3356	2716	2332	1926	1530	1238	1017	724	558	453	370	300	213	112	60	31	0

P	G	X																				
kPa	kg/m²/s	-0.50	-0.40	-0.30	-0.20	-0.15	-0.10	-0.05	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.60	0.70	0.80	0.90	1.0
15000	4000	8160	7215	6240	5517	4982	4378	3485	2844	2435	2068	1694	1412	1150	872	765	613	497	376	261	129	63	32	0
15000	4500	8411	7275	6346	5608	5132	4694	3664	2974	2533	2200	1832	1503	1302	1023	851	708	602	457	303	150	68	33	0
15000	5000	8630	7487	6412	5702	5293	4802	3781	3096	2704	2272	1860	1583	1383	1112	937	794	634	510	344	174	74	35	0
15000	5500	9053	7619	6512	5734	5295	4810	3881	3279	3001	2537	2118	1880	1545	1324	1160	979	776	605	400	206	85	40	0
15000	6000	9501	7930	6619	5787	5308	4727	3902	3402	3106	2684	2297	2043	1764	1482	1284	1117	921	723	475	241	100	46	0
15000	6500	9919	8306	6740	5905	5410	4850	3962	3529	3158	2723	2407	2210	1939	1640	1473	1256	1048	841	541	278	117	55	0
15000	7000	10446	8914	7008	6027	5529	4902	3985	3608	3198	2775	2437	2271	2052	1774	1559	1359	1143	926	601	314	135	64	0
15000	7500	11128	9361	7191	6059	5578	4914	3993	3671	3200	2800	2420	2300	2120	1820	1625	1435	1220	1010	662	344	147	69	0
15000	8000	11712	10053	7546	6111	5619	4949	4100	3757	3235	2890	2532	2356	2186	1978	1764	1551	1330	1108	727	374	158	75	0
16000	0	2869	2780	2691	2603	2556	2500	2417	2276	1978	1667	1411	1199	1036	903	820	739	668	640	535	317	165	92	0
16000	50	3101	3014	2934	2837	2785	2723	2645	2508	2242	1962	1719	1460	1271	1132	982	882	821	750	569	391	219	145	0
16000	100	3434	3308	3154	3001	2897	2804	2716	2551	2331	2102	1818	1590	1419	1254	1153	1024	951	846	617	418	244	166	0
16000	300	3612	3465	3314	3127	2988	2833	2733	2585	2414	2206	1909	1718	1562	1451	1257	1129	1019	859	618	463	259	164	0
16000	500	3761	3553	3386	3152	2997	2819	2693	2534	2417	2180	1909	1595	1406	1261	1052	926	793	598	392	286	127	90	0
16000	750	4113	3800	3588	3251	3055	2798	2610	2387	2251	1985	1703	1280	1113	978	780	694	578	432	229	150	89	69	0
16000	1000	4785	4471	4003	3460	3102	2756	2504	2201	1918	1634	1353	1039	952	814	665	530	455	325	192	90	59	45	0
16000	1500	5406	4726	4165	3659	3280	2939	2419	2111	1888	1505	1226	1005	879	671	522	364	231	168	134	67	46	33	0
16000	2000	5808	5019	4352	3777	3449	3071	2740	2250	1921	1623	1328	1118	918	715	502	244	203	172	127	84	51	28	0
16000	2500	6312	5514	4978	4407	3973	3504	2954	2494	2086	1747	1450	1213	1004	795	531	347	265	211	153	93	52	28	0
16000	3000	6858	5972	5429	4894	4332	3748	3146	2611	2209	1857	1533	1269	1101	817	655	481	380	300	216	113	57	29	0
16000	3500	7286	6326	5695	5018	4511	3907	3255	2653	2311	1956	1614	1345	1170	831	717	541	435	353	248	123	59	29	0
16000	4000	7568	6686	5875	5296	4700	4136	3392	2756	2428	2157	1828	1560	1325	1030	886	710	607	453	297	138	62	30	0
16000	4500	8015	6902	6071	5483	4889	4352	3511	2876	2569	2225	1960	1684	1465	1164	988	808	674	525	335	155	66	31	0
16000	5000	8249	7179	6183	5529	5058	4562	3707	3017	2698	2293	2024	1777	1574	1220	1041	890	731	567	377	182	72	33	0
16000	5500	8569	7489	6212	5601	5064	4609	3752	3226	2913	2638	2244	2036	1731	1424	1265	1067	870	666	427	207	84	39	0
16000	6000	9059	7714	6377	5610	5103	4624	3812	3382	3073	2798	2412	2191	1900	1600	1392	1180	981	764	491	246	99	46	0
16000	6500	9480	8189	6573	5714	5255	4650	3828	3484	3126	2883	2531	2275	2016	1716	1524	1290	1086	854	549	278	116	54	0
16000	7000	9832	8567	6874	5878	5336	4677	3850	3511	3183	2888	2549	2298	2068	1801	1573	1376	1167	933	607	314	135	63	0
16000	7500	10170	8880	7084	5947	5402	4698	3872	3520	3190	2890	2571	2325	2104	1848	1618	1440	1229	1012	662	344	147	69	0
16000	8000	10566	9241	7422	6073	5475	4741	3960	3663	3204	2928	2610	2356	2160	1938	1739	1538	1321	1098	722	373	158	74	0
17000	0	2509	2441	2374	2303	2265	2220	2152	2038	1796	1537	1318	1138	990	867	769	701	633	590	472	287	155	89	0
17000	50	2712	2642	2558	2470	2420	2363	2225	2081	1862	1608	1443	1292	1135	1023	895	794	740	678	514	343	190	128	0
17000	100	2894	2777	2652	2529	2456	2374	2232	2055	1887	1624	1444	1318	1188	1095	997	877	814	703	564	353	199	139	0
17000	300	3016	2785	2672	2535	2440	2339	2176	1996	1872	1606	1439	1331	1244	1155	1043	907	858	708	584	360	198	144	0
17000	500	3184	2888	2732	2547	2382	2271	2065	1876	1712	1556	1382	1233	1124	1027	905	769	694	553	323	250	127	90	0
17000	750	3454	3043	2824	2577	2385	2249	1925	1763	1606	1395	1230	1086	938	798	657	599	527	408	194	149	98	66	0
17000	1000	3784	3285	2991	2651	2430	2189	1934	1750	1562	1282	1136	997	825	733	591	527	457	333	151	85	58	40	0

P	G	X																				
kPa	kg/m²/s	-0.50	-0.40	-0.30	-0.20	-0.15	-0.10	-0.05	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.60	0.70	0.80	0.90	1.0
17000	1500	4561	3899	3367	2873	2647	2362	2052	1793	1593	1356	1164	972	840	652	513	369	269	195	141	86	51	31	0
17000	2000	5015	4246	3735	3298	2972	2636	2389	2008	1765	1546	1342	1148	993	837	591	355	285	240	156	98	53	27	0
17000	2500	5608	5002	4407	3873	3451	2983	2614	2215	1945	1676	1450	1253	1059	928	656	454	347	279	203	113	54	27	0
17000	3000	6124	5389	4860	4218	3698	3195	2792	2360	2069	1808	1536	1316	1146	965	758	574	437	354	253	126	56	27	0
17000	3500	6667	5739	5060	4355	3799	3384	2949	2481	2179	1907	1647	1424	1232	1002	809	646	499	445	332	151	60	28	0
17000	4000	7157	6165	5350	4589	4017	3587	3095	2609	2373	2131	1853	1632	1416	1143	966	804	653	561	397	167	63	29	0
17000	4500	7428	6328	5558	4758	4255	3792	3145	2697	2495	2252	1985	1739	1543	1249	1056	903	720	620	426	183	66	30	0
17000	5000	7652	6500	5689	4896	4496	3957	3299	2855	2594	2355	2079	1844	1643	1342	1116	972	780	662	442	199	72	32	0
17000	5500	7803	6730	5907	5060	4709	4107	3391	3137	2858	2639	2313	2073	1826	1561	1333	1120	931	728	483	226	84	38	0
17000	6000	8089	7017	6121	5261	4845	4198	3504	3225	3004	2750	2464	2226	1957	1677	1428	1246	1024	818	536	257	99	45	0
17000	6500	8416	7339	6299	5394	4948	4308	3560	3287	3065	2834	2558	2316	2069	1791	1543	1346	1121	882	577	287	116	54	0
17000	7000	8742	7594	6491	5478	5056	4401	3566	3323	3106	2852	2587	2341	2091	1820	1588	1401	1185	949	619	318	134	63	0
17000	7500	9096	7850	6622	5538	5079	4423	3621	3383	3110	2811	2601	2345	2109	1880	1616	1443	1241	1017	664	343	146	69	0
17000	8000	9357	8136	6826	5694	5100	4512	3723	3514	3113	2848	2645	2375	2125	1931	1716	1518	1314	1091	716	370	157	74	0
18000	0	2198	2136	2076	1999	1970	1955	1900	1809	1617	1402	1218	1063	936	822	732	660	599	569	434	260	138	84	0
18000	50	2377	2295	2209	2043	2002	1960	1886	1782	1647	1408	1260	1138	1042	922	824	744	684	620	474	310	177	117	0
18000	100	2416	2316	2220	2084	2003	1944	1847	1733	1653	1405	1278	1157	1065	958	886	784	744	648	521	331	185	132	0
18000	300	2566	2353	2230	2083	1952	1895	1783	1646	1558	1407	1285	1149	1076	1009	933	821	775	661	527	322	175	119	0
18000	500	2609	2392	2232	1998	1899	1775	1655	1447	1350	1196	1113	1025	938	826	732	648	579	454	297	214	142	66	0
18000	750	2878	2510	2247	1993	1892	1754	1607	1429	1277	1153	1052	903	794	680	578	516	450	334	169	144	90	49	0
18000	1000	3081	2635	2312	1971	1877	1728	1574	1448	1279	1145	1018	870	749	670	550	426	394	260	137	80	56	36	0
18000	1500	3760	3260	2858	2479	2206	2032	1847	1599	1404	1231	1102	903	794	681	524	379	274	215	151	90	53	29	0
18000	2000	4277	3648	3255	2811	2566	2287	2119	1844	1640	1469	1351	1222	1093	956	757	420	307	267	162	98	51	25	0
18000	2500	4845	4453	4036	3480	3095	2681	2407	2016	1838	1623	1470	1319	1149	1025	832	523	406	338	226	119	52	25	0
18000	3000	5472	4760	4329	3736	3279	2831	2533	2167	1945	1728	1516	1352	1216	1094	876	629	493	426	287	137	55	25	0
18000	3500	5983	5028	4457	3802	3381	2894	2615	2280	2042	1825	1550	1453	1243	1123	899	743	571	500	384	166	59	26	0
18000	4000	6459	5438	4798	4007	3533	3059	2685	2383	2241	2004	1738	1639	1446	1216	1029	876	710	621	453	183	61	27	0
18000	4500	6562	5560	4925	4189	3748	3266	2801	2496	2325	2136	1926	1736	1565	1316	1102	957	751	676	482	195	64	28	0
18000	5000	6719	5688	5048	4297	3973	3492	2895	2606	2414	2245	2083	1796	1648	1388	1186	1009	795	720	489	213	72	31	0
18000	5500	6820	5875	5205	4521	4157	3696	3053	2937	2717	2510	2265	2077	1861	1603	1360	1192	966	770	539	237	84	37	0
18000	6000	7067	6118	5412	4662	4293	3757	3123	3002	2856	2696	2421	2216	1969	1727	1465	1300	1063	861	585	266	99	44	0
18000	6500	7342	6385	5570	4764	4337	3813	3140	3018	2907	2781	2531	2305	2073	1825	1560	1376	1158	912	611	292	116	53	0
18000	7000	7625	6606	5716	4835	4412	3893	3166	3061	2921	2794	2536	2308	2080	1840	1594	1415	1208	968	640	320	133	62	0
18000	7500	7930	6835	5901	4941	4486	3929	3216	3070	2954	2636	2471	2326	2095	1875	1609	1443	1248	1022	670	342	143	67	0
18000	8000	8158	7075	6071	5107	4545	4009	3308	3110	2958	2771	2602	2356	2130	1923	1698	1501	1304	1084	711	364	152	71	0
19000	0	1874	1813	1752	1618	1586	1562	1518	1467	1326	1240	1075	971	890	769	682	617	562	521	395	235	122	74	0
19000	50	2017	1931	1782	1642	1580	1538	1474	1414	1331	1212	1093	991	895	820	726	653	602	540	407	265	156	102	0

P	G	X																						
kPa	kg/m²/s	-0.50	-0.40	-0.30	-0.20	-0.15	-0.10	-0.05	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.60	0.70	0.80	0.90	1.0
19000	100	2104	1987	1800	1645	1550	1500	1439	1402	1306	1204	1102	991	891	830	753	667	636	570	439	280	165	106	0
19000	300	2127	2000	1808	1646	1536	1467	1404	1335	1217	1138	1058	984	870	805	745	667	619	565	419	279	159	100	0
19000	500	2186	2021	1808	1606	1489	1407	1299	1231	1111	997	941	879	787	678	646	558	510	437	279	160	121	58	0
19000	750	2312	2051	1849	1608	1499	1408	1272	1179	1071	948	884	810	741	645	576	471	410	318	189	124	85	46	0
19000	1000	2466	2167	1913	1684	1556	1429	1311	1196	1090	1010	912	831	753	657	545	422	338	254	133	77	53	32	0
19000	1500	3098	2745	2407	2115	1936	1773	1591	1412	1242	1158	1056	886	789	729	633	420	298	253	140	84	46	26	0
19000	2000	3571	3184	2854	2498	2290	2074	1880	1695	1503	1385	1277	1221	1151	1056	857	591	362	276	166	92	46	23	0
19000	2500	4120	3727	3295	2930	2643	2374	2103	1854	1621	1489	1332	1289	1203	1087	902	678	445	357	228	119	48	22	0
19000	3000	4590	3977	3578	3076	2799	2488	2223	1956	1722	1568	1416	1362	1242	1127	913	696	556	443	295	140	52	23	0
19000	3500	4881	4182	3728	3194	2835	2590	2320	2081	1835	1678	1528	1452	1278	1188	976	795	601	526	391	169	56	24	0
19000	4000	5180	4435	3909	3270	2952	2712	2468	2193	2017	1850	1664	1581	1426	1274	1059	923	754	647	461	186	59	25	0
19000	4500	5309	4590	4069	3449	3122	2802	2532	2295	2088	1955	1781	1674	1535	1354	1128	978	812	696	493	205	63	26	0
19000	5000	5537	4819	4221	3575	3279	2980	2665	2483	2230	2080	1952	1751	1627	1440	1196	1063	838	740	501	217	70	30	0
19000	5500	5753	5074	4422	3758	3469	3139	2809	2657	2471	2280	2137	1957	1797	1615	1364	1207	975	786	551	241	83	35	0
19000	6000	5993	5294	4589	3869	3578	3254	2926	2813	2630	2421	2286	2118	1918	1697	1463	1327	1082	881	597	271	97	43	0
19000	6500	6242	5507	4738	3992	3697	3373	3012	2867	2721	2528	2392	2208	1995	1787	1544	1392	1171	935	626	294	114	51	0
19000	7000	6492	5669	4858	4092	3772	3444	3031	2900	2811	2605	2447	2232	2015	1812	1579	1422	1220	983	657	320	130	60	0
19000	7500	6728	5828	5001	4235	3903	3507	3068	2907	2816	2629	2487	2268	2054	1853	1596	1453	1254	1033	679	339	138	64	0
19000	8000	6952	6006	5150	4402	4063	3607	3226	3022	2882	2704	2528	2305	2094	1895	1681	1499	1297	1081	707	356	145	66	0
20000	0	1654	1497	1378	1240	1185	1179	1141	1092	992	947	900	872	787	719	646	568	493	438	347	213	94	55	0
20000	50	1692	1489	1356	1213	1172	1163	1123	1077	1004	950	898	848	780	715	659	575	528	451	345	230	118	73	0
20000	100	1706	1438	1300	1188	1163	1141	1114	1072	1028	974	914	840	784	709	656	595	540	470	343	234	137	75	0
20000	300	1739	1427	1208	1130	1110	1080	1070	1020	990	945	900	830	780	700	640	600	542	468	288	224	131	72	0
20000	500	1744	1338	1183	1030	975	940	903	879	835	797	761	729	680	624	545	488	438	388	204	153	90	53	0
20000	750	1796	1502	1237	1106	1029	968	914	810	766	730	695	637	585	550	502	444	342	292	170	109	75	41	0
20000	1000	1882	1636	1409	1200	1133	1086	1026	965	876	817	761	650	607	561	508	419	293	246	126	74	49	27	0
20000	1500	2459	2183	1889	1665	1549	1428	1318	1166	1045	982	905	835	763	700	620	439	286	224	130	75	42	22	0
20000	2000	3017	2693	2372	2088	1927	1729	1584	1395	1284	1221	1133	1046	977	872	812	611	423	268	152	89	44	21	0
20000	2500	3580	3154	2849	2542	2239	1971	1775	1612	1465	1360	1230	1154	1105	971	853	688	473	377	228	117	46	21	0
20000	3000	3946	3437	3038	2636	2359	2051	1906	1702	1562	1423	1270	1202	1157	1033	915	703	569	450	290	134	50	21	0
20000	3500	4162	3558	3067	2640	2400	2139	2011	1828	1658	1510	1380	1264	1190	1069	961	791	617	536	367	159	54	22	0
20000	4000	4261	3767	3268	2802	2543	2280	2138	1992	1875	1702	1585	1465	1341	1244	1086	920	741	649	439	178	57	23	0
20000	4500	4358	3923	3486	2992	2700	2470	2247	2101	1915	1788	1674	1539	1441	1344	1129	992	819	690	457	189	61	24	0
20000	5000	4517	4139	3648	3114	2874	2595	2381	2211	1995	1818	1716	1631	1517	1390	1167	1081	829	739	476	208	68	28	0
20000	5500	4718	4385	3876	3323	3012	2758	2579	2409	2214	2051	1957	1834	1687	1561	1328	1215	987	799	521	230	79	33	0
20000	6000	4922	4545	3983	3420	3175	2922	2691	2519	2353	2183	2082	1969	1796	1639	1413	1311	1080	884	576	259	94	40	0
20000	6500	5124	4667	4071	3515	3249	3017	2812	2638	2469	2247	2159	2024	1893	1721	1514	1362	1155	939	607	280	109	47	0

P	G	X																				
kPa	kg/m²/s	-0.50	-0.40	-0.30	-0.20	-0.15	-0.10	-0.05	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.60	0.70	0.80	0.90	1.0
20000	7000	5323	4730	4120	3536	3303	3069	2878	2731	2531	2333	2205	2098	1934	1757	1553	1404	1201	986	639	302	123	52	0
20000	7500	5538	4808	4165	3580	3336	3093	2892	2771	2599	2396	2282	2128	1964	1774	1588	1436	1244	1028	679	322	128	56	0
20000	8000	5768	4925	4220	3625	3375	3155	2951	2843	2697	2484	2345	2177	2017	1850	1667	1484	1289	1074	699	330	130	57	0
21000	0	1584	1462	1324	1222	1184	1147	1084	1008	939	904	821	733	644	570	501	440	415	366	309	194	84	45	0
21000	50	1587	1456	1301	1194	1164	1119	1062	999	938	900	823	736	685	650	578	501	457	411	303	197	99	53	0
21000	100	1589	1439	1270	1177	1124	1111	1060	992	948	894	826	739	697	668	599	527	469	417	300	198	102	55	0
21000	300	1601	1314	1133	1114	1102	1069	1037	959	925	857	801	730	700	669	600	510	473	399	278	169	97	56	0
21000	500	1617	1307	990	981	959	925	878	828	789	727	661	608	587	556	524	459	400	327	180	142	70	50	0
21000	750	1643	1411	1153	1045	1007	949	900	799	712	652	616	553	530	515	479	418	324	236	115	97	57	33	0
21000	1000	1787	1566	1328	1211	1130	1045	992	908	807	765	708	628	583	533	470	375	280	209	111	69	42	21	0
21000	1500	2261	1991	1764	1570	1422	1344	1228	1115	998	943	894	800	758	675	545	404	251	209	117	71	36	17	0
21000	2000	2689	2248	1983	1711	1594	1490	1395	1327	1225	1193	1101	971	874	812	741	526	343	230	150	88	35	15	0
21000	2500	2997	2554	2223	1903	1733	1609	1519	1426	1314	1260	1183	1109	988	900	816	623	445	349	214	102	36	15	0
21000	3000	3238	2847	2465	2068	1880	1706	1644	1547	1457	1302	1193	1170	1053	958	884	681	535	425	286	119	39	15	0
21000	3500	3393	2953	2590	2193	2012	1859	1772	1672	1543	1397	1284	1215	1130	993	933	773	601	516	343	138	42	16	0
21000	4000	3482	3160	2776	2356	2159	2004	1924	1794	1654	1541	1428	1347	1256	1155	1027	891	726	627	389	155	45	17	0
21000	4500	3532	3270	2896	2517	2289	2142	2028	1906	1752	1624	1544	1500	1348	1274	1100	973	809	674	421	167	49	18	0
21000	5000	3660	3436	3101	2646	2456	2256	2172	2016	1834	1742	1660	1596	1457	1350	1160	1063	818	711	451	181	54	21	0
21000	5500	3803	3603	3229	2831	2608	2447	2288	2165	1973	1880	1808	1726	1603	1482	1300	1184	939	793	492	199	61	24	0
21000	6000	3955	3698	3320	2917	2733	2544	2379	2256	2073	1965	1884	1823	1695	1572	1379	1277	1038	867	544	221	70	28	0
21000	6500	4116	3784	3378	2975	2801	2599	2485	2355	2203	2056	1990	1903	1780	1652	1478	1334	1100	924	579	239	78	32	0
21000	7000	4275	3839	3393	2985	2850	2658	2529	2447	2294	2117	2050	1971	1835	1693	1523	1373	1163	969	601	254	85	35	0
21000	7500	4471	3887	3394	3000	2880	2700	2589	2496	2361	2216	2129	2033	1872	1737	1566	1403	1214	1003	640	272	91	39	0
21000	8000	4689	3970	3405	3030	2900	2740	2598	2498	2410	2287	2170	2067	1902	1790	1622	1439	1260	1026	667	290	96	42	0

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10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

This report contains a compilation of over 25,000 CHF data obtained in water-cooled tubes that were used to derive the 2006 Groeneveld CHF lookup table. This compilation is based on 62 data sets that have been obtained during the past 60 years. The pertinent experimental details and possible concerns for these data sets are described. The applicability and validity of the CHF look-up table to reactor conditions of interest is also discussed. A graphical comparison of the ranges of conditions covered by these primary data and subsequently obtained supplementary data sets is also included.

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